In-Flight Suppressant Deployment Temperatures

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BACKGROUND

Top-level military aircraft specifications typically require operational performance capability over a broad temperature range. For example, V-22 requires such capability for any exterior ambient atmosphere temperature between -65°F (-54°C) and 125°F (52°C) and an interior ambient atmosphere temperature between -65°F (-54°C) and 160°F (71°C) [1]. In developing the temperature envelope for future aircraft specifications, acquisition officials and technical experts will derive requirements from *guidance* documents [2,3], which may likely be used to also derive development and testing requirements for aircraft systems, subsystems, and components (e.g., nacelle fire suppression systems, nacelle fire bottles, etc.). In previous aircraft acquisitions, a requirements document [4] was used to develop aircraft temperature envelope requirements. Therefore, what was once a requirement is now guidance, thus allowing future military acquisition program managers flexibility in specifying realistic requirements.

The temperature data that is recommended to define the low and high temperature extremes for airborne systems are world-wide air environments (WWAE) that are described in [2] (and previously [4]) as values with a 1%, 5%, 10% and 20% frequency of occurrence. In commercial aviation, standard climates in Joint Aviation Regulation 1 (JAR-1) [5] define temperatures based on arctic, temperate, tropical, intercontinental, and standard-day conditions. Figure 1 plots these climates versus the WWAEs used for military acquisition programs. With regards to low temperature requirements Figure 1 shows that the JAR-1 arctic climate generally correlates with the low temperature WWAEs, with the 1%, 5%, and 10% WWAEs being lower than the JAR-1 arctic climate and the 20% WWAE being slightly higher. Figure 2 depicts the worldwide land environments from [2], which categorizes these into four land environment types: basic, hot, cold, and severe cold.

The relevance of the aircraft temperature envelope requirement to on-board fire suppression systems, i.e., engine nacelle and auxiliary power unit (APU) fire suppression systems, is that the low temperature extreme defined for the envelope has historically been applied to drive the boiling point requirement for the fire suppression agent in the aforementioned systems. Thus in the context of the WWAEs, this boiling point requirement appears to exist to address the need to provide for in-flight fire suppression under atmospheric conditions consistent with arctic-like temperature conditions.

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14. ABSTRACT

This report describes review of DoD military fixed-wing and rotary aircraft fire mishap/incident data applicable to assess temperatures at which aircraft fire suppressants have been deployed in engine nacelle and APU compartment fires. Another model is also described, which was constructed to assess predicted nacelle compartment air temperatures at altitude, also taking into consideration aircraft airspeed, average nacelle airflow velocity, average engine case surface temperature, and average nacelle physical characteristics. An assessment is made of the model output versus some aircraft measurement data, fire suppressant boiling point criterion, as well as the history of altitude/temperature at which fire suppressants have been deployed. Additional analysis is also described that assessed aircraft operation in cold conditions, where the limiting temperature for fire suppressant release during take-off may be close to the (low) ground temperature. Risk assessments are also presented to quantify rate of occurrence of nacelle/APU fires and rates in which suppressants have been deployed taking into consideration altitude thresholds.

15. SUBJECT TERMS

Auxiliary Power Unit, APU, Boiling Point, Cold Soak, Engine Nacelle, Fire Suppressant, Fire Suppression, Halon, Halon Alternatives, Nacelle, Nacelle Airflow Temperature, Outside Air Temperature, Worldwide Air Environment

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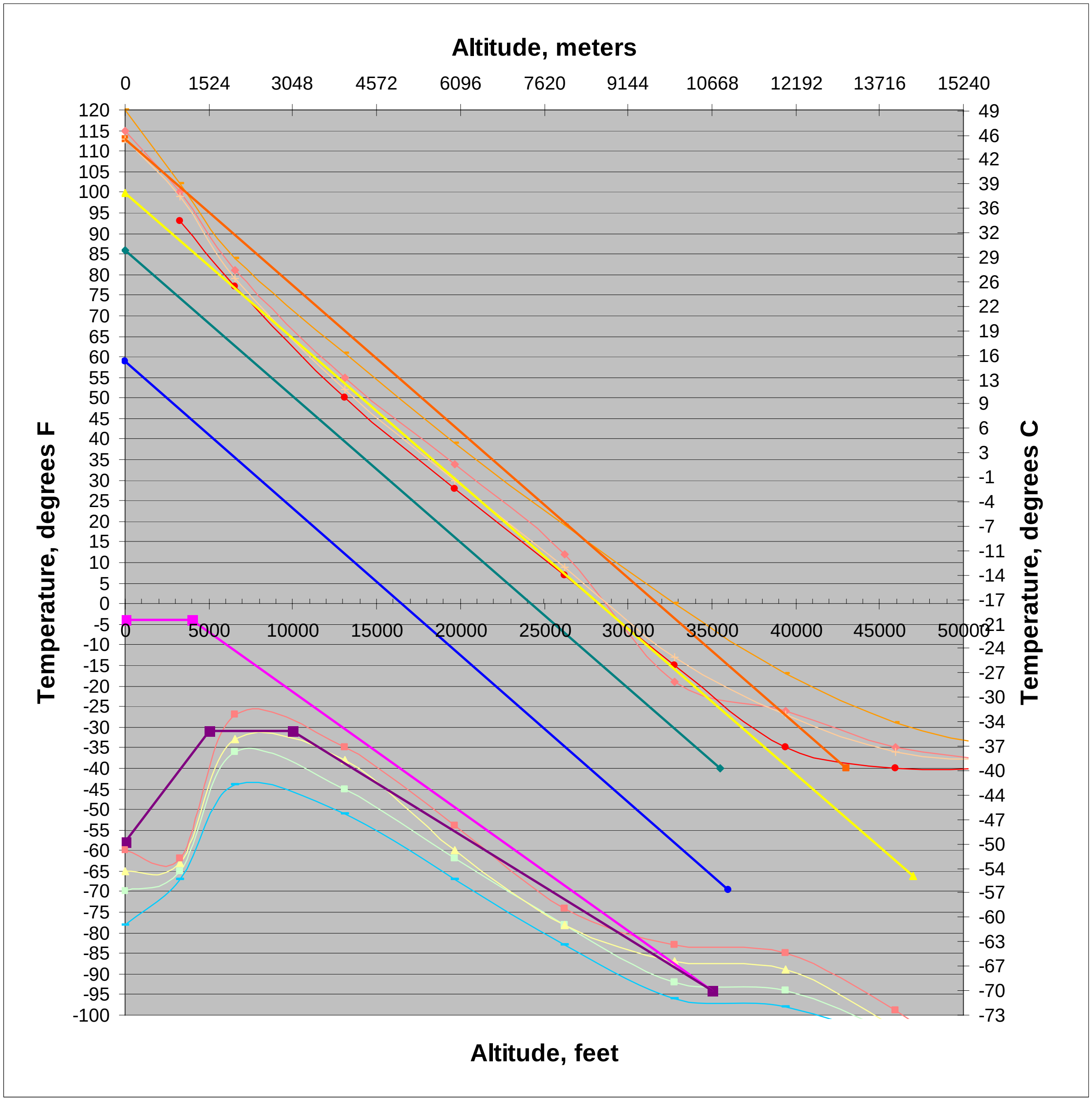


Legend	
JAR-1 Tropical Maximum	**MIL-HDBK-310 High Temperature 1%**
JAR-1/ICAO Intercontinental Maximum	**MIL-HDBK-310 High Temperature 5%**
JAR-1 Temperate and Arctic Maximum	**MIL-HDBK-310 High Temperature 10%**
JAR-1/ICAO International Standard	**MIL-HDBK-310 High Temperature 20%**
JAR-1 Tropical and Temperate Minimum	**MIL-HDBK-310 Low Temperature 1%**
JAR-1 Arctic Minimum	**MIL-HDBK-310 Low Temperature 5%**
	MIL-HDBK-310 Low Temperature 10%
	MIL-HDBK-310 Low Temperature 20%

Note: ICAO is the acronym for International Civil Aviation Organization.

Figure 1. JAR-1 Standard Climates vs. MIL-HDBK-310 WWAEs

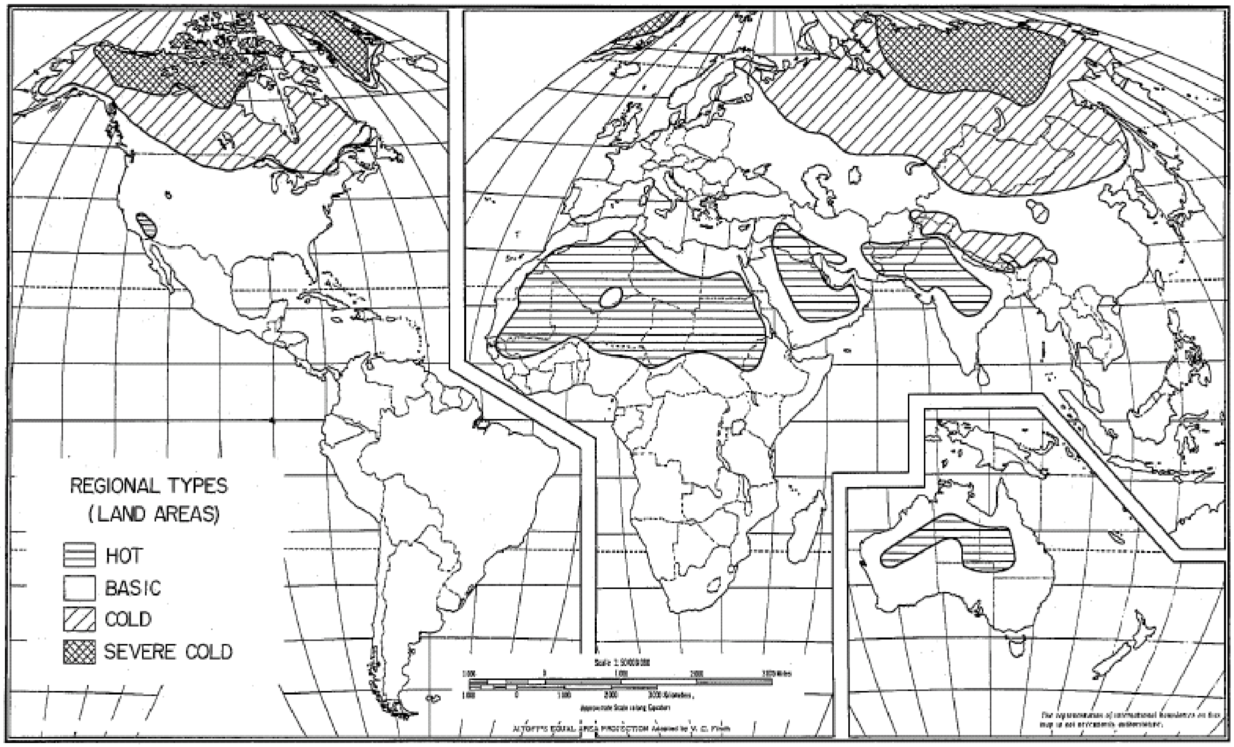


Figure 2. MIL-HDBK-310 Land Environments

With regard to ground fire suppression, land environments indicated as cold or severe-cold climates are the likely environments in which cold-soak conditions prior to aircraft startup would exist. Reference [2] indicates a low-temperature 1% frequency of occurrence of -50°F (-45.6°C) for cold land environments and a low-temperature 20% frequency of occurrence of -60°F (-51°C) for severe-cold land environments. Designers of legacy aircraft would develop fire suppression systems whose requirements [6,7] were tailored to halon 1301 properties to likely assure fire suppression performance at such temperature conditions.

During the engineering and development process for a military aircraft, trade-offs are inevitably made that take into consideration performance requirements versus operational contexts, weight, cost, schedule, and safety. Such trades are assessed and categorized by applying programmatic and safety risk matrices. Military aviation program managers then take into consideration such assessments during their decision making process to select a particular trade option. For example, the USAF C-103J and Navy KC-130J programs elected to use a high-boiling-point agent, halon 1211, for engine nacelle fire suppression to minimize developmental impact associated with system changes that would be needed to accommodate non-ozone depleting halon alternative suppression agents. (For years, many legacy C-130 aircraft have also used a high-boiling-point agent, halon 1011.) Even though neither a Department of Defense (DoD) nor a Federal Aviation Administration (FAA) certification requirement was identified for halon 1211, a United Kingdom Ministry of Defense nacelle fire suppression requirement of 10.5% had been identified [8]. This requirement is indicated to include a safety factor over a minimum halon 1211 concentration for fire extinguishment (7.1%). However, technical rationale was compiled to support a *lower* certification requirement of 6.5%, which is recognized by the U.K.

Civil Aviation Authority [9]. In the context of low temperature WWAEs and ceilings for these aircraft (legacy C-130s: 19,000-33,000 feet; C-130Js: 28,000 feet), use of such agents would be considered not technically feasible. Boiling points for these agents are 25°F (-9°C) for halon 1211 and 151°F (66°C) for halon 1011 [10]. (It is interesting to note that existing commercial aircraft specifications [11,12] indicate that "safe limits" for "unwinterized" halon 1011 or halon 1301 cylinders are -65°F to 200°F.) Justification for likely acceptable performance at low temperature (i.e., -40°F) asserted that in order to generate a vapor-phase extinguishing atmosphere, the vapor pressure of halon 1211 at -40°F (-40°C) must be greater than the partial pressure required for a halon 1211 extinguishing concentration [9], and data was provided that indicated this was the case..

Boiling point (or T_b) of a fire suppression agent has been used as one of the criterion to guide the search for new halon alternative chemical fire suppressants under the DoD Next Generation Fire Suppression Technology Program (NGP) [13]. Currently, this criterion is -40°C (-40°F). It was also one of the parameters considered during research efforts that identified pentafluoroethane (HFC-125) as the best near-term alternative to halon 1301 for use in aircraft nacelle fire suppression system applications [14]. However, even during those efforts it was recognized that, when operational contexts were considered such as the likely temperature environment within an operational engine nacelle at the time of discharge of a fire suppression agent, the typical low temperature performance requirement could be a candidate for a performance trade. Discussions in this regard related to minimum nacelle operating temperatures were indicated to range from less than 0°F (-17.8°C) to 100°F (37.8°C) [15]. Review of nacelle compartment airflow temperature data for a variety of aircraft platforms indicates temperatures ranging from -1.3°F (-18.5°C) to 525°F (273.9°C) [16 through 20]. Though this data may not address every operating environment, they suggest that even at low outside air temperatures (OAT) it is probable that the typical operational engine nacelle compartment temperature will be greater than -40°F (-40°C).

It must also be considered that for years, even decades, high T_b agents have been used in military aircraft nacelle fire suppression systems. In addition to halon 1011 on C-130 aircraft, this also includes halon 1202 on C-5 and F-111 aircraft [21]. Their successful implementation and history is likely attributable to several factors such as 1) the fact they are brominated halogens, 2) nacelle operating temperatures, 3) applications that may *benefit* from the high T_b characteristic, e.g., single-phase flow in long distribution runs, 4) freezing points well below temperatures likely to be experienced on ground and at altitude, and 5) distribution system design that ensures adequate distribution throughout the nacelle. This last factor was also emphasized and applied in the development of the F/A-18E/F HFC-125 nacelle fire suppression system [22]. *The obvious conclusion is that both low- and high-boiling-point agents are likely to realize higher probability of success as distribution is optimized.*

With regards to the potential for nacelle fires at low temperatures on the ground (i.e., OAT less than an agent's T_b), procedures can be written to mitigate the risk of fire during engine start. Guidelines for cold weather operation have long existed for commercial aviation [23]. For military aircraft, flight manuals will provide procedures for cold weather operation and typically require the presence of a "fire guard" or "fire watch" during engine start-up (i.e., a person standing by with a fire extinguisher in the event of a start-up-related fire). The flight manual for

the Navy KC-130J aircraft [24], which utilizes halon 1211, a high boiling-point agent for nacelle fire suppression, requires that "*If the ambient temperature is expected to be -40°C (-40°F) or below, ensure ground support equipment and personnel are available at destination or plan to provide needed support.*" Specific procedures are also provided for engine starting at such temperatures taking into consideration whether or not the aircraft has been preheated. Thus the likelihood of a nacelle fire during engine start at OATs below an agent's T_b, for which no fire guard is present and for which a catastrophic fire event occurs, becomes a hazard for which safety risk is accepted by the aviation program. Typically, such risk is accepted when it has been assessed as a low safety risk.

There is previous analysis of military aircraft experience regarding release of nacelle fire suppression agents [25], the purpose of which was to quantify halon discharges at altitude for the purpose of evaluating discharge frequency and quantity of agent discharged below and within the ozone layer. Combining both fixed-wing and rotary aircraft discharges that analysis indicates:

- Approximately 77% occurred between 0 and 10,000 feet, and approximately 92% occurred between 0 and 20,000 feet.
- Over 60% of all discharged agent was accounted for by only three of the thirty military aircraft platforms covered by the study. These three platforms have altitude ranges that extend beyond 20,000 feet but are contributors to the frequency of discharges below 10,000 feet.
- Over 25% of all agent discharged was high-boiling-point agent (i.e., halons 1011 and 1202).

A heretofore operational context that has not been investigated, and is thus the subject of this study, is whether temperature conditions at the time of agent release correlate with the typical boiling point temperature requirement. These include OATs, nacelle operating temperatures, cold-soak temperature conditions and cold climatic extremes. Based on review of nacelle compartment airflow temperature data for a variety of aircraft platforms, it is reasonable to assume that nacelle compartment temperatures are well above boiling points of fielded nacelle fire suppression agents. When considering that historic release of nacelle fire suppression agents has typically occurred below 20,000 feet, with over 75% occurring below 10,000 feet, and that the likely occurrence of fire while either cold soaked or while in cold climatic extremes is likely a low probability event, the likelihood of not extinguishing a nacelle fire after agent release and realizing a catastrophic event under such conditions suggests strongly that the combination of these events has a low probability. *The implication of the preceding is that selection of a fire suppression agent whose boiling point is compatible with cold soaking or a cold climatic extreme results in a protection capability against events whose likelihood of occurrence has a very low probability, and that halon alternative agents with higher boiling points are not likely to appreciably increase risk under such conditions.*

TECHNICAL APPROACH

The technical approach for this project consisted of four elements:

1. Obtain and review aviation Safety Center fire incident data to extract, if possible, altitude and/or outside air temperature (OAT) information that would permit characterization of OAT conditions during which agent release has historically taken place. Based on this data it may be possible to assess probability of agent release under conditions that are likely to be well above an agent's boiling point.
2. Construct and validate an in-flight nacelle air temperature model to estimate likely nacelle compartment air temperature for given altitude, outside air temperature, general engine surface temperatures, and aircraft airspeed conditions. Such a model would be useful in allowing system designers to assess compartment temperatures at altitude relative to an agent's boiling point.
3. Evaluate implications of aircraft cold-soak conditions, particularly during aircraft takeoff.
4. Assess safety risk, considering the findings in the preceding elements, of utilizing a fire suppression agent whose boiling point is much higher than of those agents commonly fielded today in military aircraft (i.e., halon 1301).

SAFETY CENTER DATA

Aviation fire incident data was obtained for the years 1980 through 2002 from the U.S. Army, Navy and Air Force Safety Centers. Each Safety Center was also asked to provide as part of that data information for altitude, outside air temperature, and location associated with each incident. In addition, data obtained for this effort was also correlated with previous efforts related to aircraft halon discharges [25] and aircraft halon fire extinguishing systems effectivity [26,27]. Table 1 summarizes the number of incidents provided by the Safety Centers.

Table 1. Number of Incidents

Service, Aircraft Type	**Army**	**Navy**	**Air Force**
Fixed Wing	88	1,212	3,932
Rotary	465	834	98

The fire incident data was reviewed to determine whether agent release occurred and to identify the altitude and OAT associated with each release. Only agent releases associated with discharge of systems protecting the following were considered: engine nacelle, auxiliary power unit (APU), auxiliary power plant (APP), and gas turbine compressor (GTC) compartment. For incidents that provided altitude data but did not include temperature data, the standard atmosphere model indicated in Figure 3 was applied to estimate OAT. <u>Rationale for use of this model is provided later in this paper under discussion of results</u>. For incidents without altitude and temperature information, the methodology for assuming flight altitude based on aircraft flight phase from previous work [25] was applied. This is summarized in Table 2. Military Internet sites were also used as needed to obtain aircraft ceiling altitudes as well as hover in ground effect and out of ground effect for various rotary aircraft platforms. Once an altitude was assigned, the OAT at release was then determined by applying the standard atmosphere model. Ground fire incident locations and in-flight fire nearest locations were also compared to the climatic land environments in Figure 2.

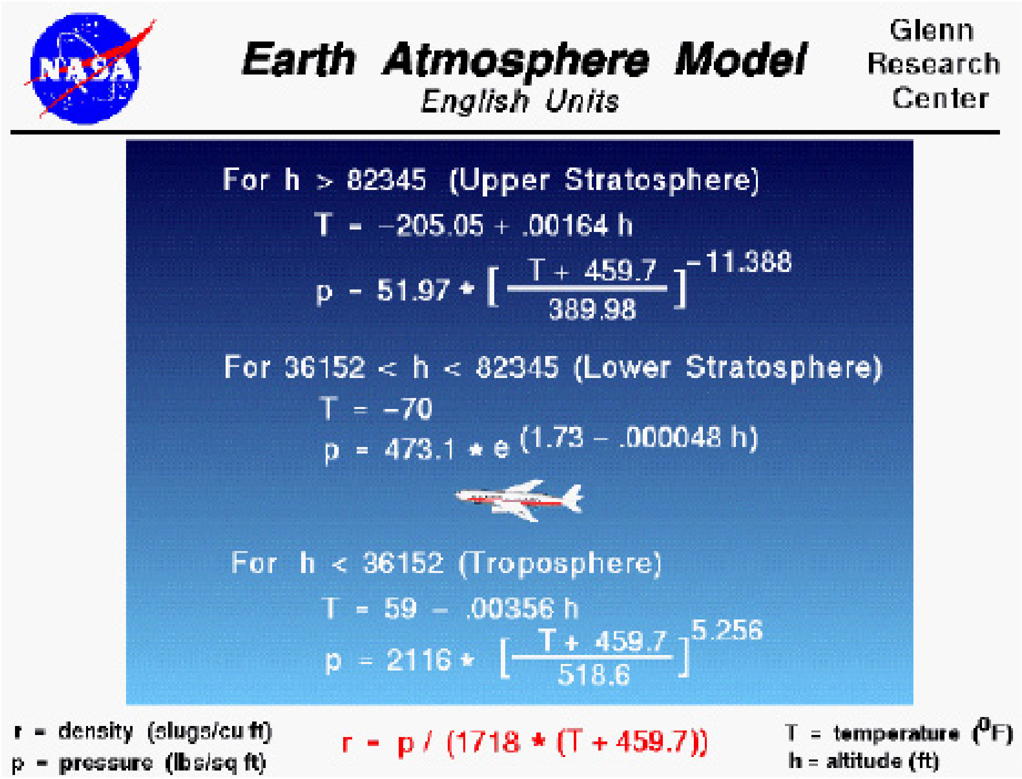


Figure 3. Standard Atmosphere Model

Table 2. Altitude Assumptions Applied from Previous Halon Discharge Analysis [25]
(Used only when no altitude data was available.)

Phase	Altitude Range (km)	Assumed Altitude (km)	Assumed Altitude (ft)
Low	below 1.5	1.00	3280.84
Range work	below 1.5	1.00	3280.84
Bomb run	below 1.5	1.00	3280.84
After takeoff	below 1.5	1.00	3280.84
Cruise-fighter	6.06 - 7.58	6.82	22375.33
Cruise-cargo	9.14 - 10.67	9.90	32480.32
Refueling	8.79	8.79	28838.58

Pilot Response

Fire incident data was also reviewed to ascertain pilot response time in effecting agent discharge. The purpose of this effort was to provide background in support of NGP efforts to model fire suppressant dynamics in cluttered weapon systems compartments, e.g., engine nacelle compartments. During planning efforts it was questioned how long does a fire burn before the pilot effects agent discharge. Response time was categorized qualitatively as follows:

- **Normal –** the fire incident narrative indicated that the pilot response followed typical emergency procedures for effecting agent release without delay. After receipt of a fire warning, the pilot isolates the affected compartment, which removes fuel flow to that compartment, and arms the fire suppression system. The pilot then confirms that he still has the fire warning and has some secondary indications of the fire condition. Upon these confirmations the pilot then discharges the agent into the compartment.
- **Slow –** the fire incident narrative indicated that the pilot response followed typical emergency procedures for effecting agent release but there was some delay prior to discharging agent. For example, after shutting off fuel flow and arming the suppression system, the pilot still is receiving the fire warning but can't obtain any other secondary indication. The pilot then may ask crew members to investigate, and after a brief period of time the fire is confirmed and the pilot discharges the agent.
- **Long –** the fire incident narrative clearly indicated that the pilot response was protracted. In some of these narratives response times in excess of 1 or 2 minutes are indicated.

IN-FLIGHT NACELLE AIR TEMPERATURE MODEL

An in-flight nacelle air temperature model was constructed to estimate nacelle air temperature during flight conditions. The model uses the U.S. Standard Atmosphere 1976 data on pressure-altitude, temperature, and viscosity [28]. The model treats the nacelle as an air heat exchanger, and it computes the terminal temperature difference based on average, bulk values. The inlet conditions at the ram scoop are computed to be the stagnation properties for the given flight conditions, and these are taken to be the same as those inside the nacelle, close to the inlet. The effect of conduction and radiation heat transfer is assumed negligible; i.e., heat losses from air through the nacelle wall to the ambient outside by convection and conduction.

Inputs to the model are as follows:

- d_c Average nacelle clearance, feet
- d_n Average nacelle diameter, feet
- v_{avg} Average nacelle ventilation air velocity, feet/second
- H Altitude, feet
- L Nacelle length, feet
- T_S Average engine surface temperature, °F
- V Aircraft true airspeed, knots

Constants and conversion factors utilized within the model are as follows:

- c_p, specific heat for air at constant pressure, 0.24 BTU/lb-mol°F
- g, acceleration due to gravity, 32.174 ft/second^2
- M, molar mass of air, 28.966 lb/lb-mol
- Pr_{air}, Prandtl Number for air, 0.73, assumed constant
- R, universal gas constant, 1545 (ft-lb)/(lb-mol°R)
- 1 BTU = 778 ft-lb

- 1 knot = 1.689 feet/second
- 1 hour = 3600 seconds
- °F = °R – 460

Computational relationships utilized within the model are as follows:

Ambient outside air temperature, T_a, and ambient pressure, p_a, were derived from [28] by linear regression analysis:

$$T_a = 518.7 - 0.003567(H), \text{°R} \quad (1)$$

$$p_a = 2094.8 - 0.07006(H) + 6.97\text{x}10^{-7}(H^2), \text{lbs/ft}^2 \quad (2)$$

Ambient atmospheric air density, ρ_{air}, is derived for ambient temperature and pressure by the following:

$$\rho_{air} = (M/R)(p_a/T_a), \text{lbm/ft}^3 \quad (3)$$

The nacelle inlet air temperature is determined by:

$$T_{in} = [(1.689V)^2 - (v_{avg})^2]/[2g(778)c_p], \text{°R} \quad (4)$$

The thermal conductivity of air, k, was fitted by a linear interpolation between -148°F (-100°C) and the freezing point of water, resulting in the following:

$$k = 0.0091 + [0.0049(T_{in} + 148)/180], \text{BTU/hr-ft-°F} \quad (5)$$

The absolute viscosity of air within the nacelle, μ, is determined from Equation 51 from [28]:

$$\mu = 2.2(10^{-8})(T_{in}^{\ 1.5})/(T_{in} + 198.72), \text{lb-second/ft}^2 \quad (6)$$

Nacelle stagnation pressure, p_2, nacelle air density, $\rho_{nacelle}$, and nacelle surface area, S, are determined as follows:

$$p_2 = p_a + \rho_{air}(1.689V)^2/2g, \text{lbs/ft}^2 \quad (7)$$

$$\rho_{nacelle} = (M/R)(p_2/T_{in}), \text{lbm/ft}^3 \quad (8)$$

$$S = \pi d_n L, \text{ft}^2 \quad (9)$$

The Reynolds number, Re, for the nacelle is estimated as:

$$Re = (\rho_{nacelle})(v_{avg})(d_n)/\mu g \quad (10)$$

The convective heat transfer coefficient, h, is determined using equation 9-10a from [29]:

$$h = 0.023(Re^{0.8})(Pr_{air}^{0.4})k/d_c, \text{ BTU/hr-ft-°F} \qquad (11)$$

The temperature rise within the nacelle, ΔT, is determined by:

$$\Delta T = hS[T_S + 460 - 0.5(T_{in} + T_{exit})] / [\rho_{air}(3600)(v_{avg})(\pi/4)((d_n + d_c)^2 - d_c^2)] \text{ , °R} \qquad (12)$$

The exit temperature, T_{exit}, is then simply:

$$T_{exit} = T_{in} + \Delta T, \text{ °R} \qquad (13)$$

Calculations for ΔT and T_{exit} are iteratively calculated in incremental changes of 0.001.

To evaluate in-flight conditions generally representative of likely flight and nacelle operating conditions, the model was evaluated against the high and low operational parameter settings listed in [30] for nacelle configuration (length), clearance, airflow, and surface temperature. Settings for these parameters from [30] are shown in Figure 4. An additional surface temperature condition of 400°F was also evaluated. Conditions were evaluated for altitudes of 0 feet, 1,000 feet, 5,000 feet, and in subsequent increments of 5,000 feet up to 30,000 feet. Rationale for applying the model only up to 30,000 feet is provided later in this paper under discussion of results.

COLD SOAK CONDITIONS

A literature review was performed to identify existing work related to evaluation of aircraft cold soak conditions. Two Transport Canada reports were identified [31,32], which provide information relative to aircraft wing surface temperatures during ground operations during Canadian winter and aircraft cold soak conditions after flights at altitude. A general conclusion was that wing temperature surveys of aircraft returning from flights at altitude failed to find evidence of significantly cold-soaked wing conditions (flights were conducted in North America: Canada, Alaska). The reports also provide data that indicate the following relative to non-de-iced spot wing temperatures:

- Below 0°C (32°F) OAT, wing temperatures were generally *higher* than OAT. The temperature difference generally ranged from 2°C at 0°C OAT to slightly greater than 6°C at -25°C OAT.
- Above 0°C (32°F) OAT, wing temperatures were generally *lower* than OAT.
- Radiative cooling on the ground (i.e., aircraft parked overnight in cold weather) is more likely than in-flight conditions to result in cold-soak conditions. Possible wing-to-OAT differential due to radiative cooling may range from -6°C at 0°C OAT and reducing to -2°C at -25°C OAT [33].

PARAMETER	SYMBOL	LOW SETTING	HIGH SETTING
Extinguishant	EXTNGT	HFC-227ea	Halon 1301
Extinguishant Discharge Location	ALOC	Side	Top
Extinguishant Distribution (either use of a simple distribution tube or "dumped" directly into the outer nacelle)	DIST	Dump	Dist Tube
Extinguishant Bottle Temperature	BTMP	-20° F	160° F
Ventilation Air Pressure	APRS	14.5 psia	17.0 psia
Ventilation Air Temperature	ATMP	100° F	275° F
Extinguishant Bottle Pressure	BPRS	400 psi	800 psi
Clutter (simulated by ribs protruding from core and nacelle)	CLUT	1-inch high rib	2-inch high rib
Configuration (simulating longer or shorter nacelle)	CONF	Short (123 inches)	Long (170 inches)
Clearance (distance between outer nacelle and engine core)	CLEAR	6 inches	12 inches
Fire Location in Nacelle	LOCA	Bottom	Top
Fuel	FUEL	MIL-H-83282	JP-8
Fuel Temperature	FTMP	100° F	200° F (83282) 325° F (JP-8)
Internal Ventilation Air Mass Flow Rate	INTE	1.25 lb/s	2.75 lb/s
Preburn Time	PREB	5 sec	20 sec
Surface Temperature	STMP	175° F	1300° F

Figure 4. Nacelle Operational Parameter Settings [30]

The Transport Canada data includes a flight profile for a flight at altitude in Alaska during which wing surface temperatures were recorded. The cruise altitude is not specified but is likely to be approximately 30,000 ft based on aircraft type. In review of the temperatures recorded it is interesting to note the following:

- At the time lift off from the ground occurs (t = 0), measured wing temperatures are *higher* than both OAT and the initial wing temperatures.
- During takeoff climb, there is one test point where there is a temperature *increase* of approximately 5°F over the first five minutes, before it begins to decrease. (All other measurements are noted to begin to immediately decrease.)
- 15 minutes after takeoff, wing temperatures are generally -5°F (-20.5°C).
- 60 minutes after takeoff, wing temperatures are generally -10°F (-23.3°C)

- Wing temperatures are noted to warm to approximately 20°F (-6.67°C) in 15 minutes time during descent to final landing

With regards to potential halon alternative candidates, an issue has been raised during the NGP and in previous research efforts that cold-soak conditions were of concern with regard to the boiling point of an agent and agent discharge under such conditions, especially during takeoff, hypothetically supporting the need for an agent with a boiling point of -40°F (-40°C) or lower. Except for the radiative cooling condition, the aforementioned data suggest that temperature conditions of an operational aircraft are likely to be higher than the cold soak temperature conditions, suggesting that aircraft component temperatures are also likely to be higher. It is interesting to note that the lowest OAT for which cold-soak data is recorded is -13°F (-25°C).

To analyze the concern of fire suppression agent and system component temperatures under cold or extreme cold temperature conditions during takeoff, a model was constructed to estimate stagnation temperature conditions during takeoff. The premise is that for agent bottle(s), distribution lines and components not located near/within heated compartments but adjacent to exterior surfaces, the stagnation temperature should provide a reasonable estimate of likely temperature conditions of components adjacent to the exterior surfaces. Assumptions applied in constructing the model include:

- If the aircraft has been deiced, it is assumed that there is minimal to no heat transfer effect to components adjacent to exterior surfaces by the time takeoff occurs, based on discussions with Transport Canada.
- The radiative cooling condition is not considered because aircraft are likely to be started and warmed up prior to takeoff. Thus in cold or severe-cold environments, component temperatures are likely to be at least the same as OAT.
- The first case assumes an initial OAT for cold/severe-cold environments based on the JAR-1 Arctic Standard Climate profile, and then the profile is applied during takeoff climb. This is assumed to estimate a lower bound profile.
- A second case assumes an initial OAT of –40°F (–40°C) and maintains this temperature during takeoff climb until OAT changes in the JAR-1 Arctic profile.
- The third case assumes an initial OAT of –40°F (–40°C) and applies a bias condition based on difference of wing skin temperature to OAT described in the Transport Canada work. The JAR-1 Arctic Standard Climate profile is then applied during takeoff climb with the bias condition continuously applied to estimate a potential upper bound profile.
- Speed conditions are sub-sonic, less than Mach 1, and there are no aerodynamic heating affects.
- In calculating stagnation temperature, equation 2.58 from [34] was applied:

$$T = T_a + KV^2/7592,\ °K, \tag{14}$$

where:

- T is the stagnation temperature, °K
- T_a is the ambient temperature, °K
- K is the temperature recovery factor, which can range from 0.7 to 1.0

- V is the true airspeed, knots
- Conversion factors utilized were:
  - °K = °C + 273.15
  - °F = 1.8°C + 32

RISK

The Safety Center data reviewed under this effort along with previous work [26,27] were considered to assess likelihood of agent release and likelihood of aircraft loss due to not suppressing an engine nacelle fire. Assessment of risk is done considering guidelines in military system safety standards [35] and service-specific guidelines [36-38].

RESULTS

SAFETY CENTER DATA

Results presented are based on NAVAIR System Safety interpretation of aviation fire mishap data provided by the Army, Navy, and Air Force Safety Centers.

Location

Incident data was first reviewed for the geographic locations where fires (and releases) occurred. Table 3 summarizes the results of this review. This review was performed to:

1. Assess occurrence of fire in cold or severe-cold environments, as defined in [2], for incidents occurring on the ground.
2. Assess occurrence of fire for incidents occurring in flight or characterized as in-flight for aircraft operating *nearest to locations* in cold or severe-cold environments.

Table 3. Percentage of Fire Incidents Occurring in Geographic Cold or Severe-Cold Environments

Service, Aircraft Type	Army	Navy	Air Force
Ground	0	1.5%	1.1% (a)
In-Flight	< 1%	< 1%	2.7% (b)

(a) From data categorized as ground fire incidents only.
(b) From data categorized as in-flight fires only but also includes incidents on ground characterized as flight fire incidents.

Rationale for Estimating In-Flight Temperatures Using the Standard Atmosphere Model

Generally, the fire incident data provided by the Safety Centers included altitude information in terms of mean sea level (MSL), above ground level (AGL), or flight level (FL). Altitude expressed in these terms is typically in terms of pressure altitude, while the Standard Atmosphere

is based on geopotential altitude. Figure 5 illustrates the variation of ambient pressure versus pressure altitude and geopotential altitude on standard-day and non-standard-day temperature conditions. The implication with regards to estimating OAT using the Standard Atmosphere Model is that cold temperature conditions may be lower than estimated on non-standard-days or if altitude is based on pressure altitude. However, the percentages indicated previously in Table 3 suggest strongly that applying the MIL-HDBK-310 cold WWAEs or the JAR-1 Arctic Climate profile as the basis for estimating temperature conditions would not reflect operational experience.

Safety Center data that included *both altitude and OAT* for which agent release occurred is plotted in Figure 6. Distribution of those events indicates releases typically about or above the Standard Atmosphere profile. Below the profile, the lowest OAT was indicated is 26°F (-3.3°C), which occurred at ground level. For the highest altitude below the profile, 5,400 feet, the lowest OAT is indicated as 35.6°F (2°C).

Figure 7 plots other fire incidents for which Safety Center data included *both altitude and OAT* but in which there may have been no engine or APU fire or for which there was an engine or APU fire but *no* agent release. The majority of the incidents at altitude occur above the profile and below 20,000 feet. Only one incident is indicated that is beyond the profile at altitude and below 0°F (-17.8°C), which occurred at 40,000 feet, -77.8°F (-61°C). This only incident for which *both altitude and OAT* were provided that occurred below -40°F (-40°C). The highest altitude below the profile and above 0°F (-17.8°C) occurred at 6,400 feet with an OAT indicated as 14°F (-10°C). There are three incidents indicated at zero altitude (on the ground) and below 0°F (-17.8°C). These occurred with OATs at -13°F (-25°C), -18°F (-27.8°C), and -27°F (-32.8°C).

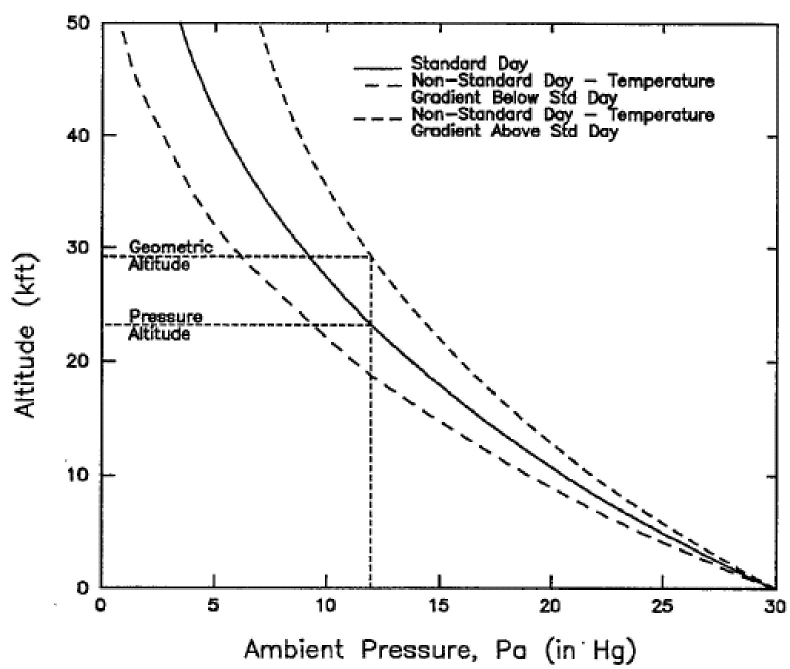
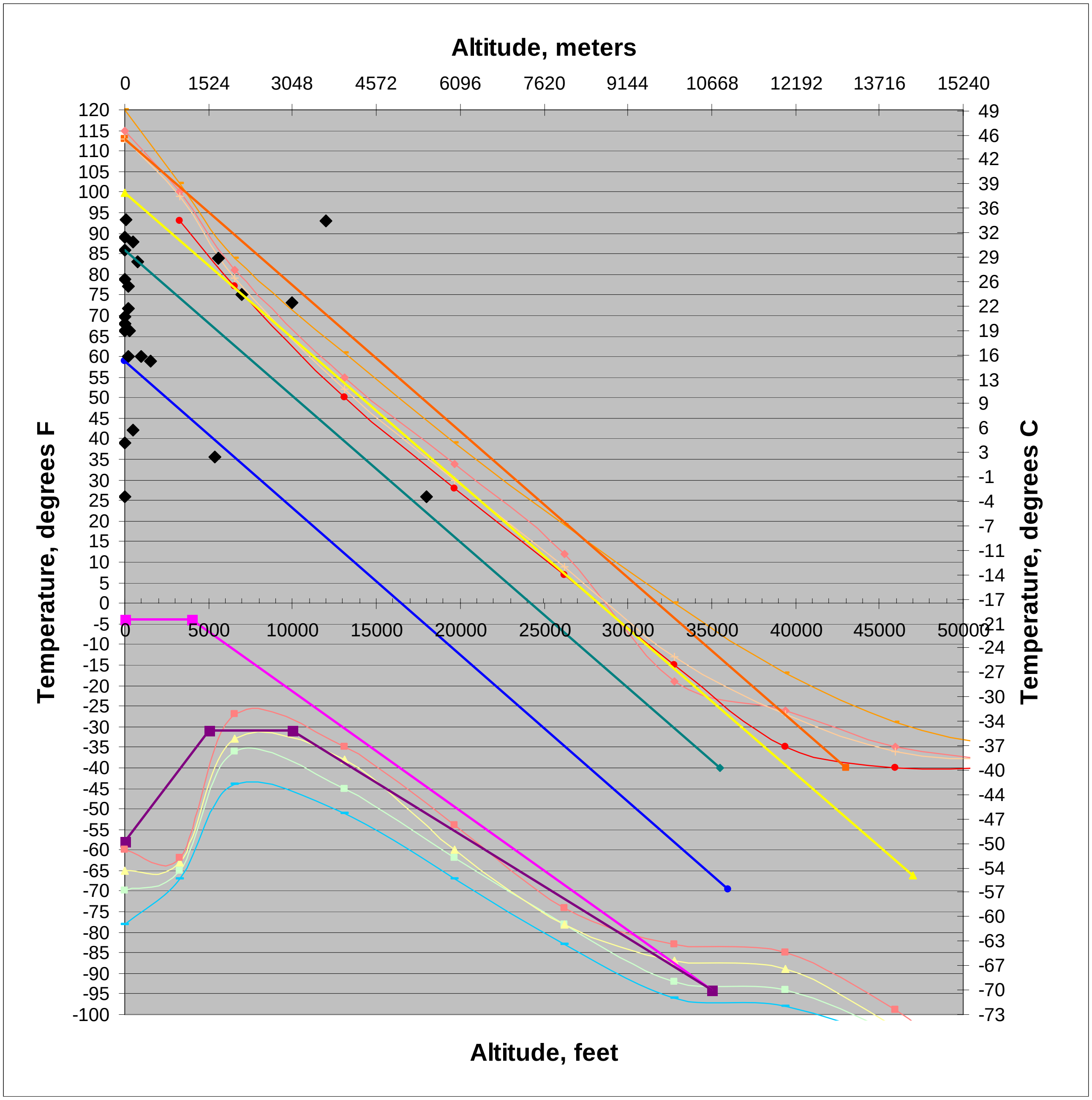


Figure 5. Variation of Ambient Pressure versus Pressure and Geopotential Altitudes on Standard-Day and Non-Standard-Day Temperature Conditions [39]

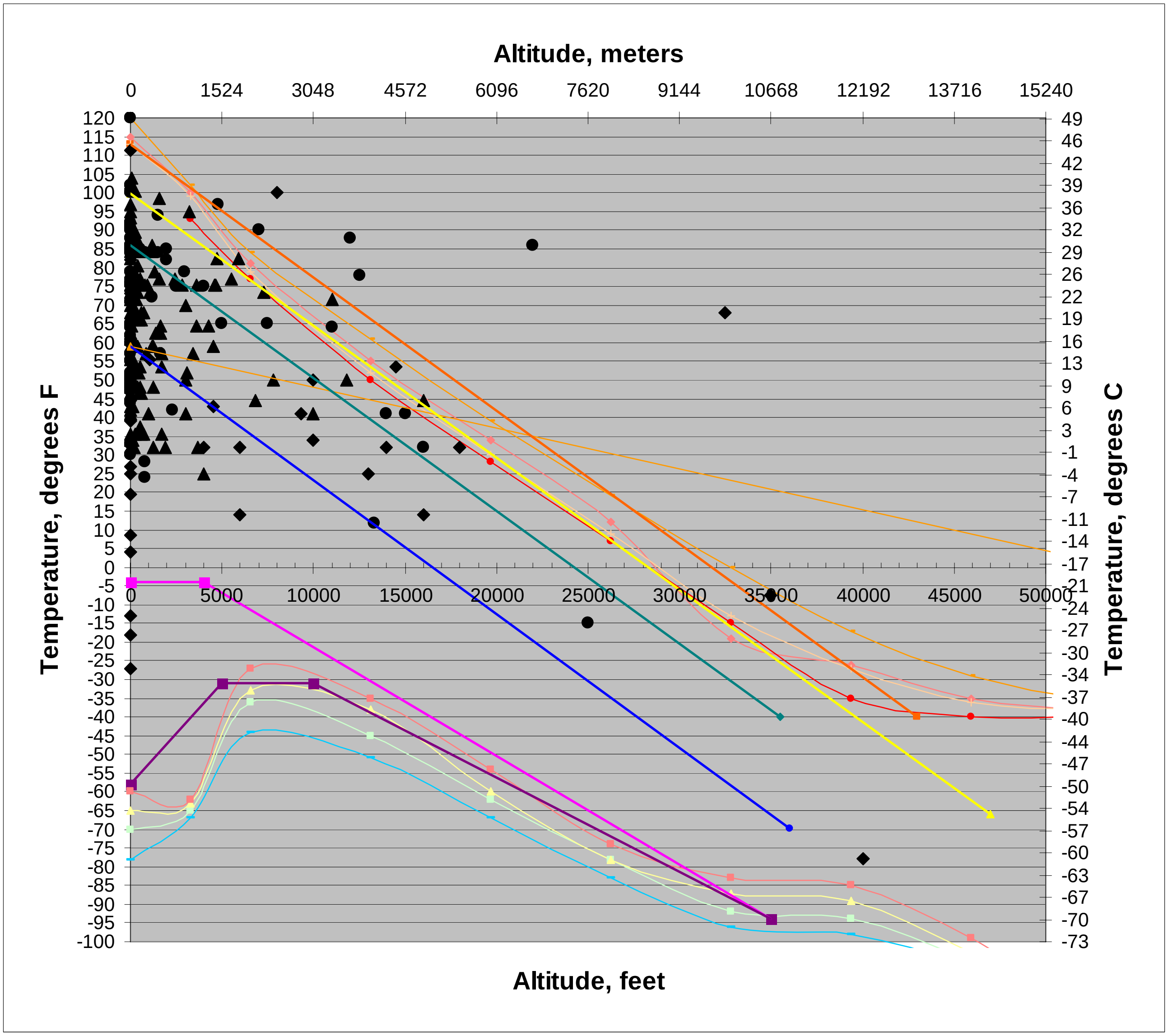


Notes: (1) Agent releases are black data points

(2) Refer to Figure 1 for identification of profiles depicted.

(3) The dark blue profile is the Standard Atmosphere profile.

Figure 6. Plot of Standard Climate Profiles and WWAEs and Agent Releases for which Safety Center Data Provided both Altitude and OAT



Notes: (1) Black data points are other fire incidents for which Safety Center data provided both altitude and OAT
(2) Refer to Figure 1 for identification of profiles depicted.
(3) The dark blue profile is the Standard Atmosphere profile.

Figure 7. Plot of Standard Climate Profiles and WWAEs and Other Fire Incidents for which Safety Center Data Provided both Altitude and OAT

An additional consideration for using the Standard Atmosphere Model for estimating OATs during suppressant release is fuel flammability limits. Figure 8 depicts flammability limits of Jet-A and Jet-B versus altitude and standard atmospheres (JP-8 limits are similar to limits for Jet A, and JP-5 limits are slightly higher than those depicted for Jet-A.). Though ignition is dependant on many variables, Figure 8 suggests that for military aircraft using JP-8 and JP-5

fuels, attaining the flammability limits is more likely at atmospheres above the Standard Atmosphere.

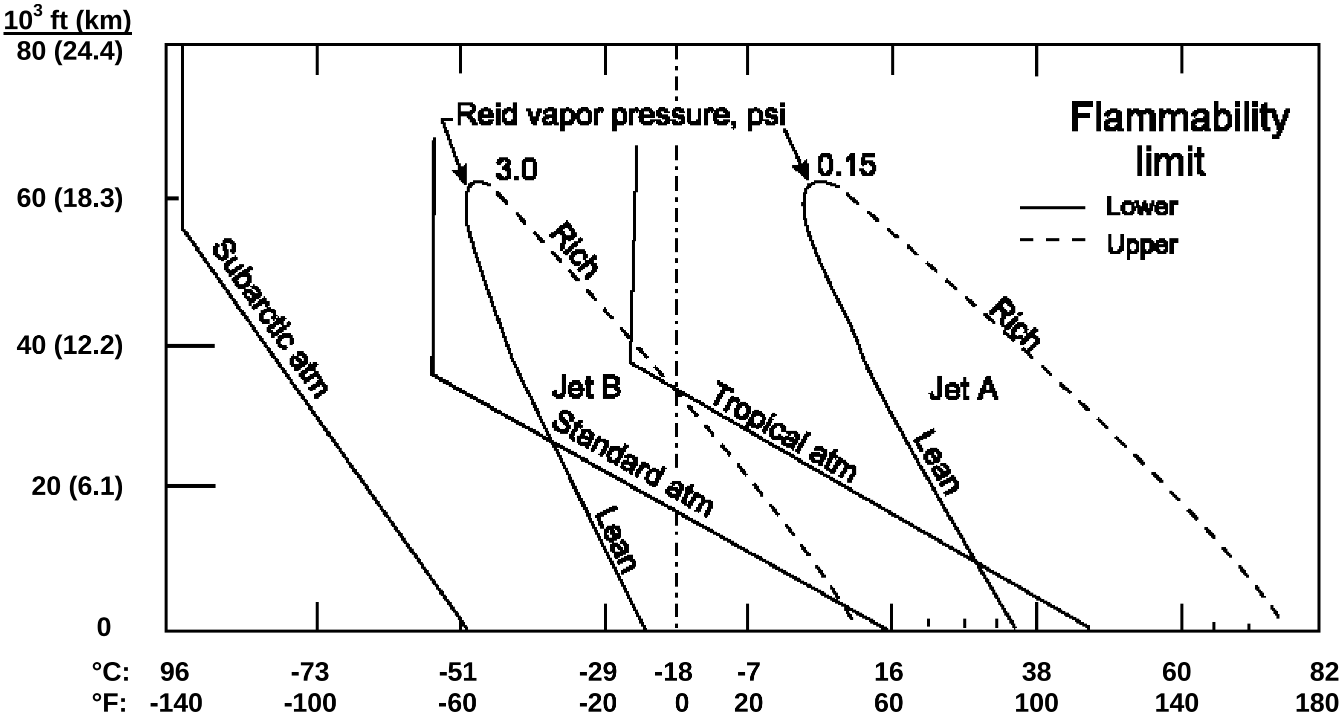


Figure 8. Flammability Limits of Jet-A and Jet-B Fuels versus Altitude and Standard Atmospheres [21]

Based on review of the findings presented in Table 3 and Figures 6 through 8 it was concluded that the Standard Atmosphere Model could be used to provide a reasonable estimate for OATs at which suppressant releases at altitude have occurred.

Summary of All Suppressant Releases (Includes Estimated OATs)

Figures that follow summarize altitude and OAT for all suppressant releases identified in the fire incident data provided by the Safety Centers. This includes incidents for which Safety Center data included both altitude and OAT, incidents for which altitude data was provided and OAT was estimated using the Standard Atmosphere Model, and incidents for which both altitude and OAT were estimated. Figures 9 through 16 summarize fixed-wing aircraft suppressant release by altitude and OAT thresholds. Figures 17 through 21 summarize the same for rotary aircraft suppressant release. Table 4 summarizes suppressant release by Service aircraft category (fixed-wing and rotary). No occurrence was found in which currently fielded high-boiling point suppressants failed to discharge due to cold temperature conditions (i.e., frozen agent).

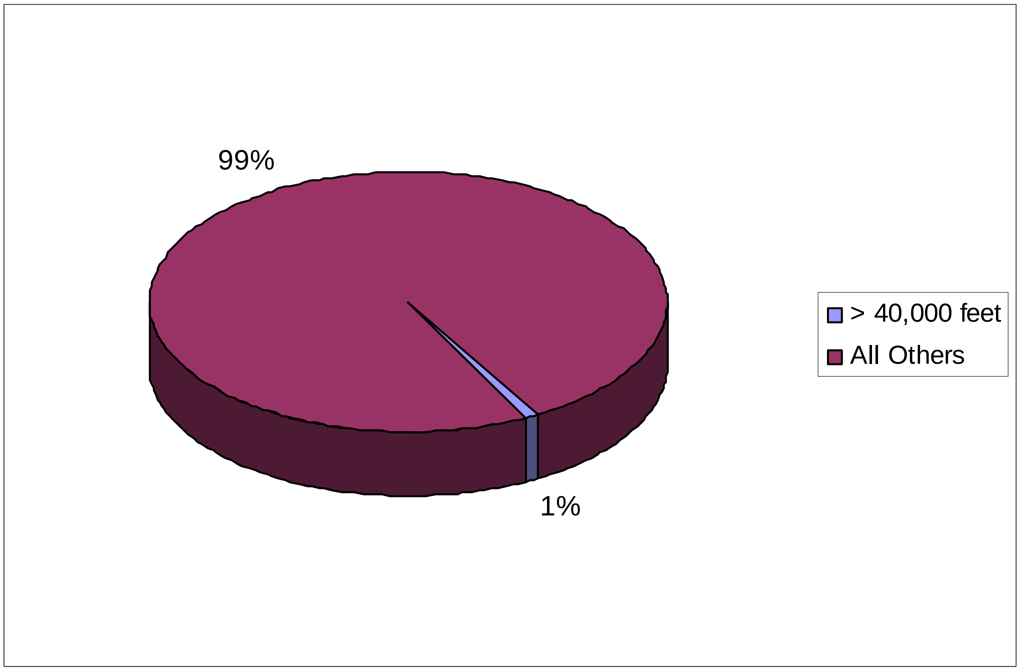


Figure 9. Percentage of Fixed-Wing Aircraft Suppressant Releases at or Greater than Altitude of 40,000 feet

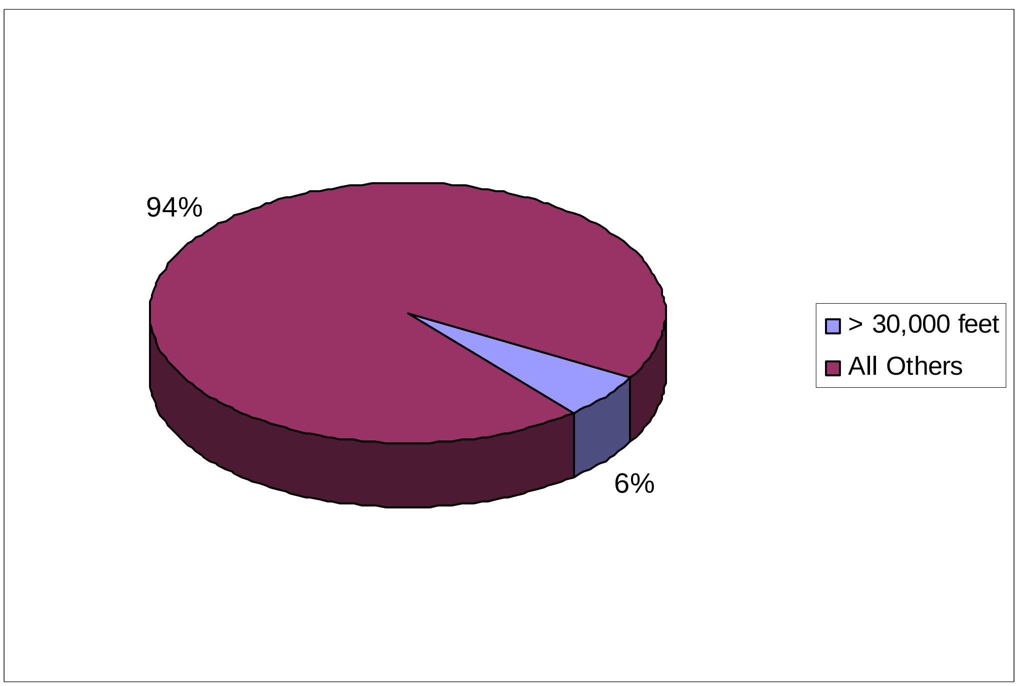


Figure 10. Percentage of Fixed-Wing Aircraft Suppressant Releases at or Greater than Altitude of 30,000 feet

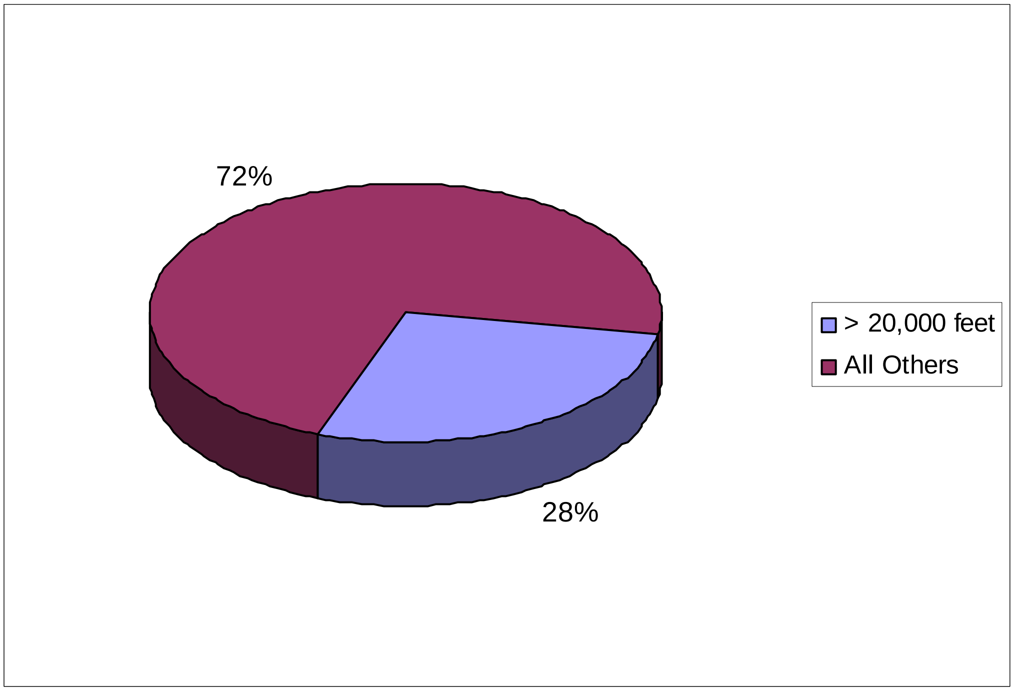


Figure 11. Percentage of Fixed-Wing Aircraft Suppressant Releases at or Greater than Altitude of 20,000 feet

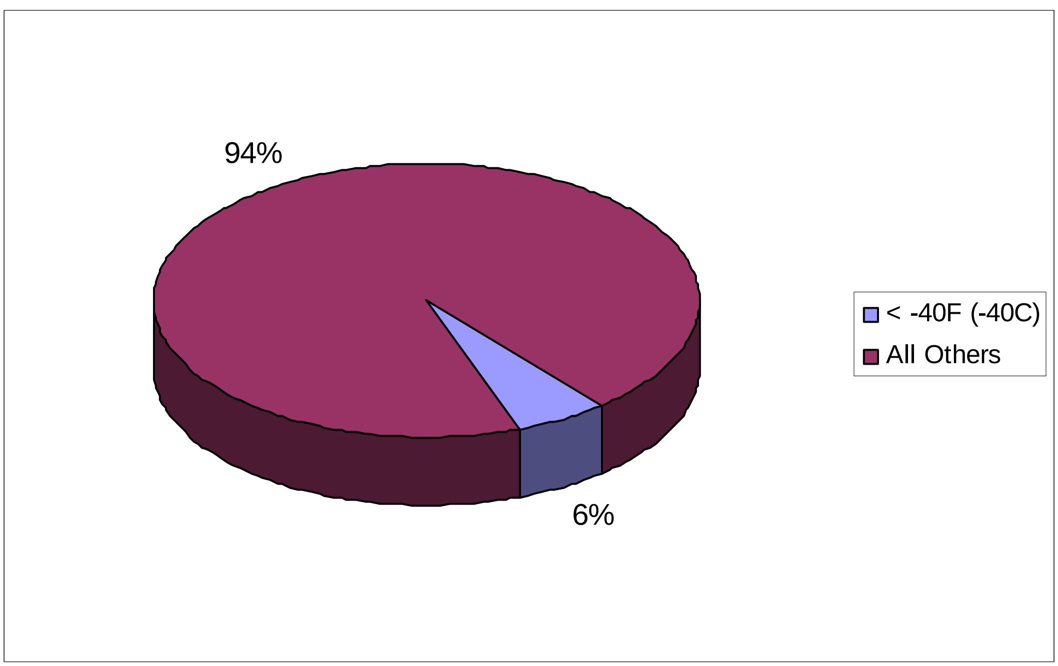


Figure 12. Percentage of Fixed-Wing Aircraft Suppressant Release at or Less than OAT Equal to -40°F (-40°C)

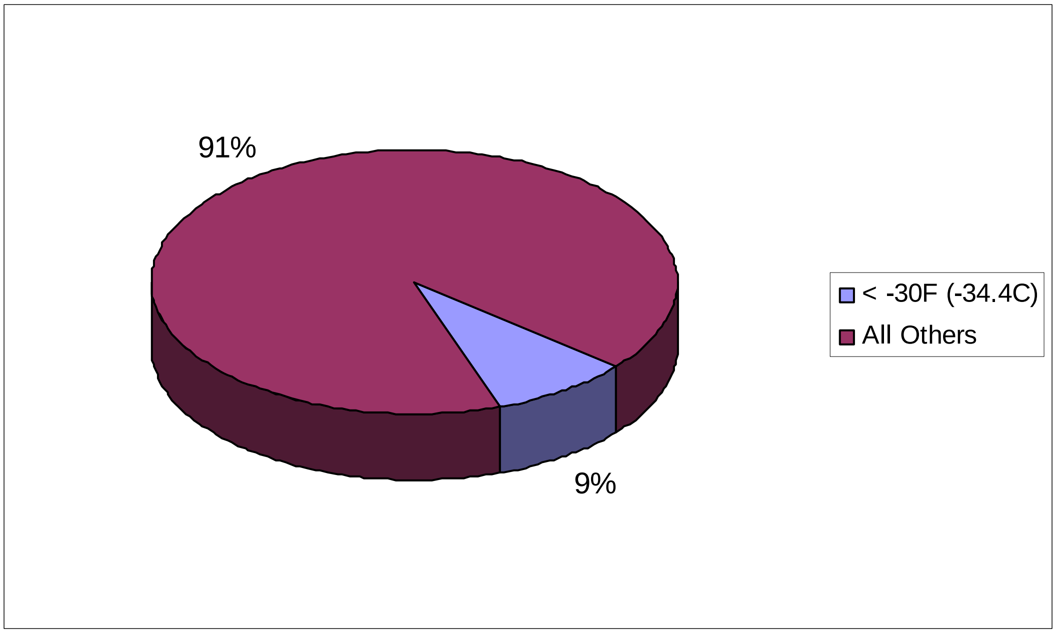


Figure 13. Percentage of Fixed-Wing Aircraft Suppressant Release at or Less than OAT Equal to -30°F (-34.4°C)

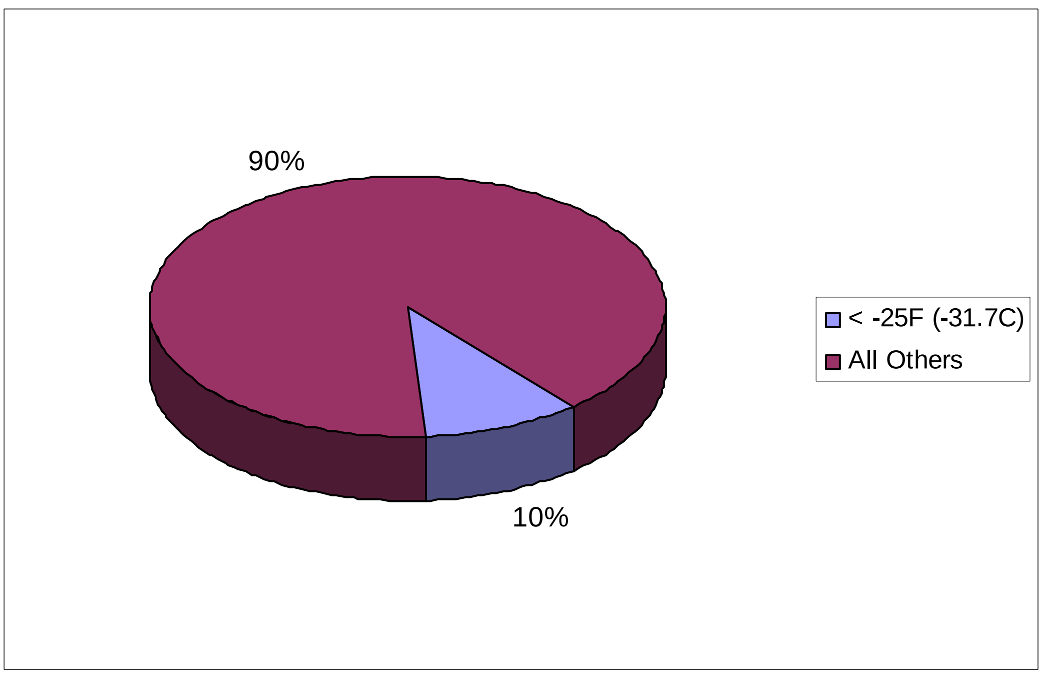


Figure 14. Percentage of Fixed-Wing Aircraft Suppressant Release at or Less than OAT Equal to -25°F (-31.7°C)

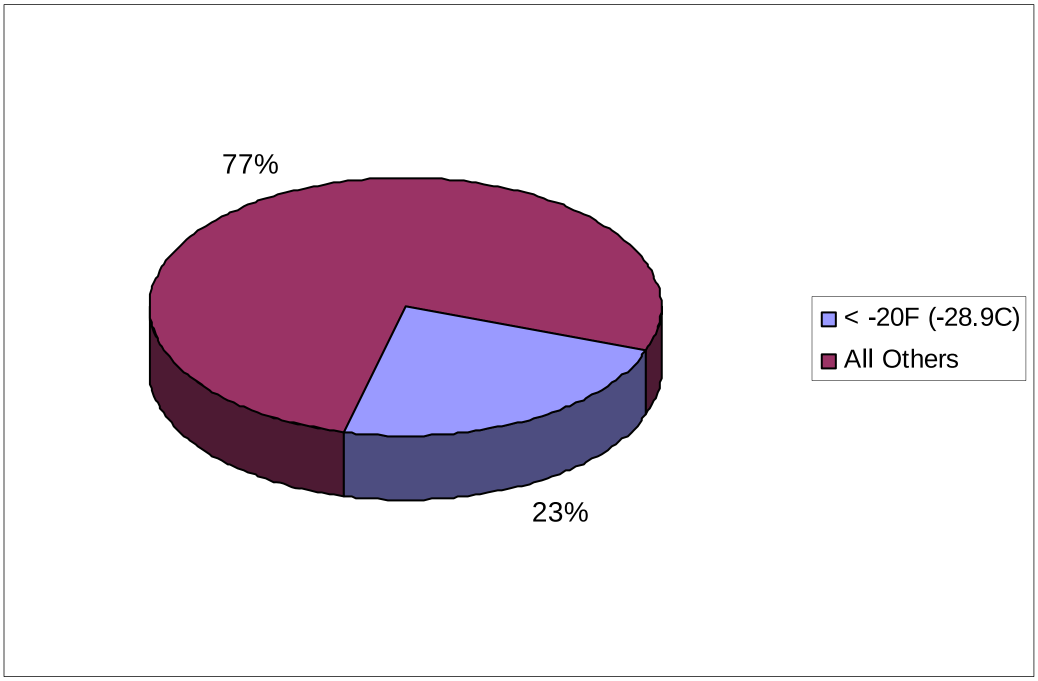


Figure 15. Percentage of Fixed-Wing Aircraft Suppressant Release at or Less than OAT Equal to -20°F (-28.9°C)

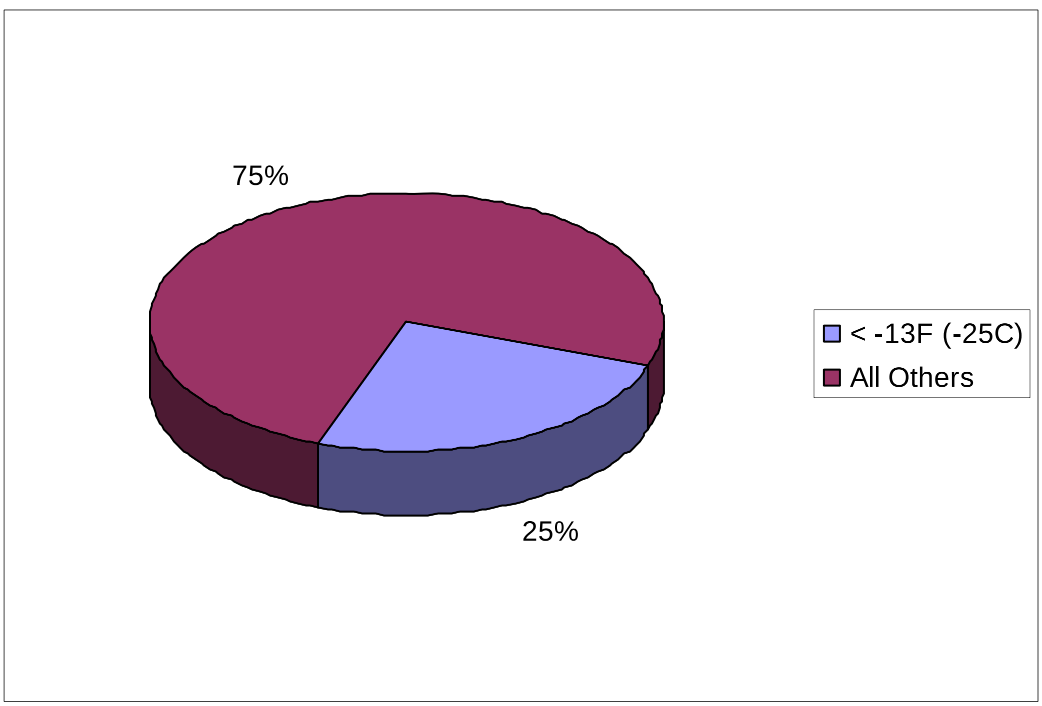


Figure 16. Percentage of Fixed-Wing Aircraft Suppressant Release at or Less than OAT Equal to -13°F (-25°C)

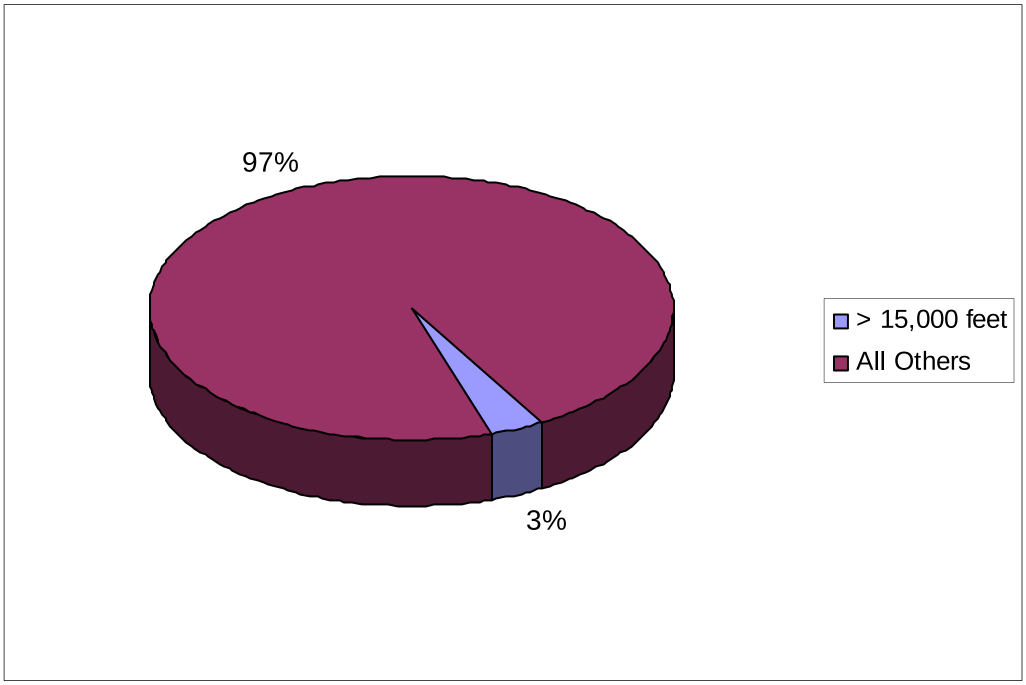


Figure 17. Percentage of Rotary Aircraft Suppressant Releases
at or Greater than Altitude of 15,000 feet

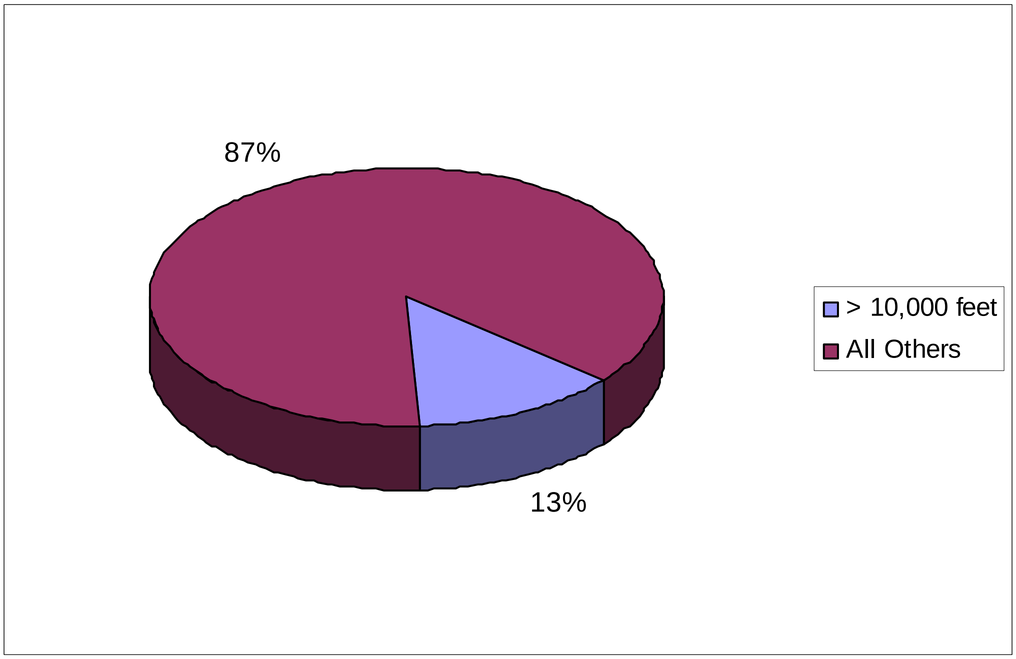


Figure 18. Percentage of Rotary Aircraft Suppressant Releases
at or Greater than Altitude of 10,000 feet

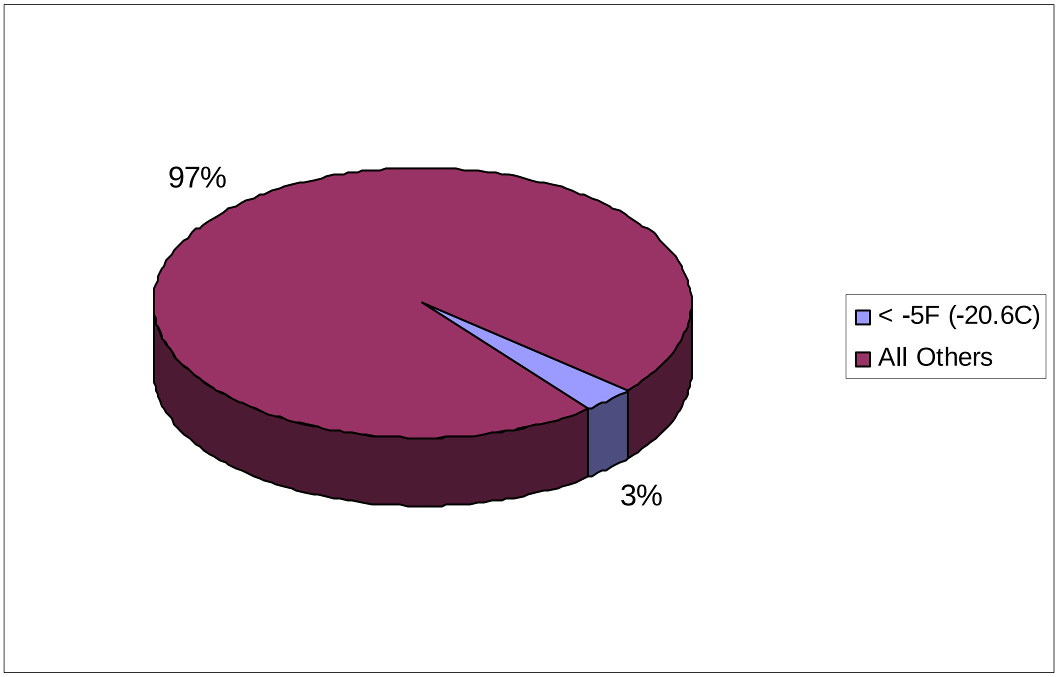


Figure 19. Percentage of Rotary Aircraft Suppressant Release at or Less than OAT Equal to -5°F (-20.6°C)

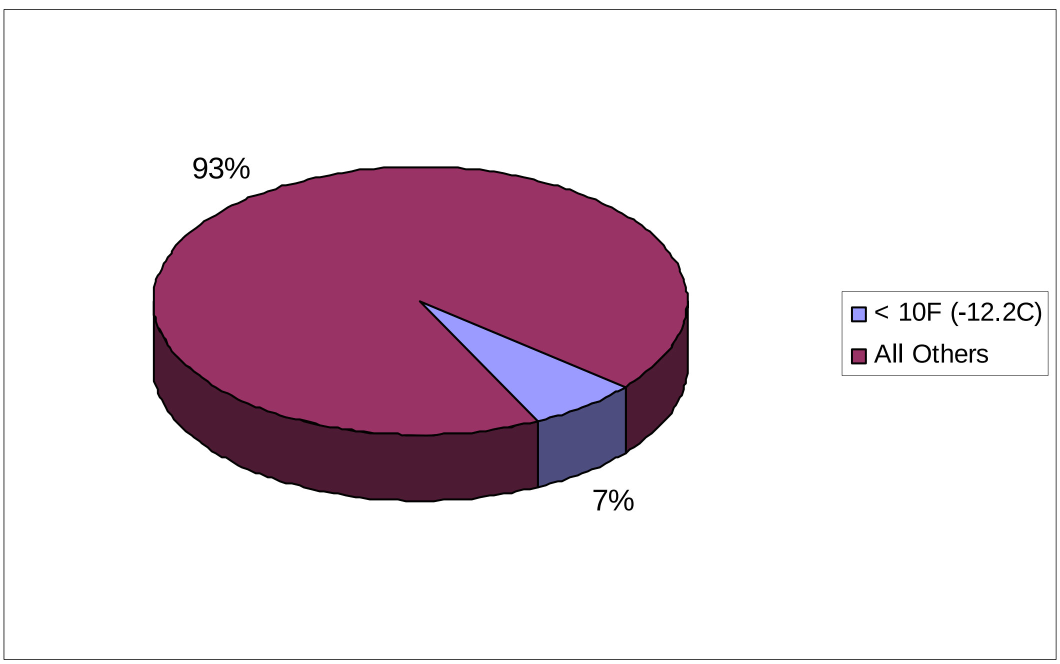


Figure 20. Percentage of Rotary Aircraft Suppressant Release at or Less than OAT Equal to 10°F (-12.2°C)

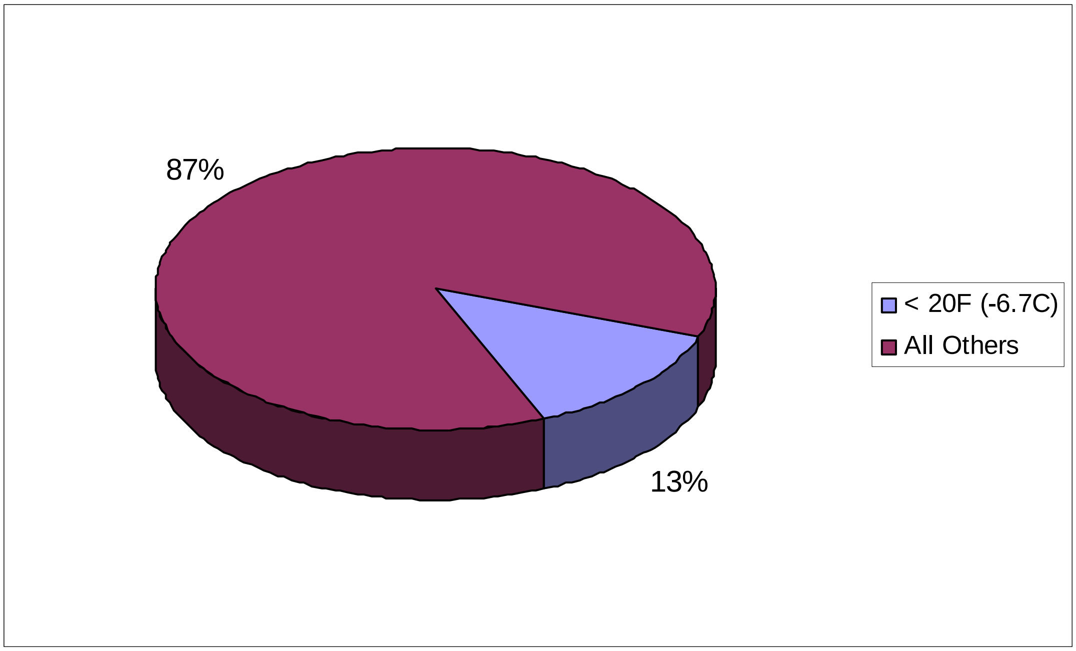


Figure 21. Percentage of Rotary Aircraft Suppressant Release at or Less than OAT Equal to 20°F (-6.7°C)

Table 4. Summary of Suppressant Release by Service Aircraft Category
(Fixed Wing and Rotary)

Army	**Navy**	**Air Force**
Fixed-wing aircraft: • One release identified at 20,000 ft, another at 25,000 ft. Temperature conditions estimated as -12.2°F (-24.6°C) and -30°F (-34.4°C), respectively • One release identified at 16,000 ft, another at 18,000 ft. Temperature conditions estimated as 2°F (-16.6°C) and -5.1°F (-20.6°C), respectively • Remainder of releases at 10,000 ft or lower. Temperature conditions estimated to be >45°F (7.2°C)	Fixed-wing aircraft: • *No releases identified at ≥30,000 ft* • Two releases identified at ≥20,000 ft, temperature conditions estimated as -16°F (-26.7°C) and -34°F (-36.7°C) • One release identified at 18,000 ft, another at 19,000 ft. Temperature conditions estimated as -9°F (-12.8°C) and -5°F (-20.6°C), respectively • Remainder of releases at 12,000 ft and lower, temperature conditions estimated to range between 16°F (-8.9°C) and 93°F (33.9°C)	Fixed-wing aircraft: • Overwhelming majority of releases <30,000 ft • Two releases identified at ≥40,000 ft, temperature condition estimated as -70°F (-56.7°C) • 11 releases identified at ≥30,000 ft, temperature conditions estimated to range between -47.8°F (-44.3°C) and -70°F (-56.7°C) • Many releases (31%) at ≥20,000 ft, temperature conditions estimated to range between -33.6°F (-36.4°C) and -12.2°F (-24.6°C) • For releases at <20,000 ft, temperature conditions estimated to range from 2°F (-16.7°C) to 59°F (15°C)
Rotary aircraft: • Majority of releases < 15,000 ft. • Two releases identified at 19,150 ft, temperature condition estimated as -9.2°F (-22.9°C) • Remainder of releases at 11,000 ft and lower, temperature conditions estimated to range between 19.8°F (-6.8°C) and 93.2°F (34°C)	Rotary aircraft: • No releases identified above aircraft service ceilings, which range between 10,000 ft and 19,150 ft for all but one aircraft type. Temperature conditions estimated as -3°F (-19.4°C) to 23°F (-5°C) for this ceiling range • One Navy rotary platform has a ceiling of 27,900 ft , but no releases were identified for this type	Rotary Aircraft: Lowest temperature condition estimated for release from a rotary aircraft discharge was 5.6°F (-14.7°C)

Pilot Response

Figure 22 summarizes pilot response time to initiate agent release based of review of Navy fixed-wing fire incident data and application of the qualitative categorization of response time as discussed under Technical Approach. Review of previous work to assess effectivity of currently-fielded halon 1301 systems [26,27] indicates that there is not a one-for-one correspondence of pilot response to fire-out success (i.e., effectivity was noted to be much less than 100%).

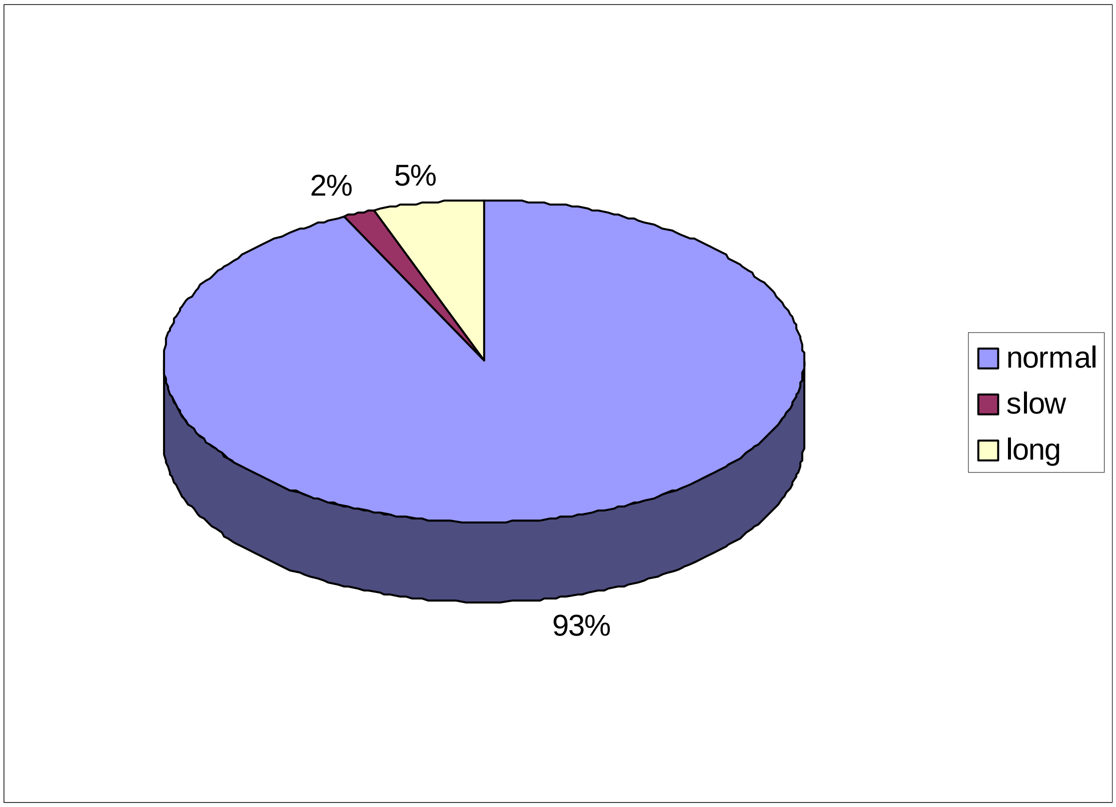


Figure 22. Pilot Response Time to Initiate Agent Release During
Navy Fixed-Wing Aircraft Engine Nacelle Fires

IN-FLIGHT NACELLE AIR TEMPERATURE MODEL

The nacelle air temperature model described under Technical Approach was applied to 1,025 cases, bounded by altitude to 30,000 feet. Model runs were limited to this altitude for 2 reasons: 1) only 6% of all fixed-wing aircraft fire suppressant releases were indicated to have occurred above 30,000 feet, and 2) though the Standard Atmosphere Model for the tropopause has a ceiling of 36,152 feet, only 1.7% of all fixed-wing aircraft fire suppressant releases were indicated to have occurred above this ceiling. The OAT ranged from -48.3°F (-44.6°C) to 58.7°F (14.8°C) based on the model, and input conditions for aircraft airspeed, altitude, nacelle physical dimensions, nacelle airflow velocity, and nacelle surface temperature were as described under Technical Approach. Results are indicated in Figures 23 and 24, which depict peak nacelle temperature versus altitude for the two airspeed conditions modeled: 50 knots and 400 knots.

In review of the model output, 88% of the cases indicated nacelle air temperatures greater than 0°F (-17.8°C). Closer review of the remaining 12% of the cases (those less than 0°F) were noted for input conditions at 20,000 ft or greater, and 89% of these cases (89% of the 12%) were noted for at airspeeds of 50 knots. The implication of these cases is that 1) they are not credible for typical military rotorcraft, which typically have operational ceilings less than 20,000 feet, and 2) they are not credible for typical military fixed-wing aircraft that have nacelle fire suppression capability (e.g., fighter/attack aircraft, cargo transports, patrol aircraft) as a 50-knot airspeed would be typically *below* stall speed for these aircraft. The remaining 11% (i.e., 11% of the 12%) were noted for input conditions at 30,000 feet and 400 knots and indicated nacelle air temperatures ranging between -10°F (-23.3°C) and -12°F (-24.4°C), which equated to 1.5% of all cases modeled.

It must be noted that if the non-credible cases are then removed from consideration the actual percentage of total cases indicating nacelle air temperatures greater than 0°F (-17.8°C) becomes greater than 88%. So modeling additional cases up to the ceiling of the Standard Atmosphere Model for the tropopause is likely to result in additional nacelle air temperatures less than 0°F (-17.8°C), but it is likely to not dramatically impact the percentages described.

The results indicated appear counterintuitive, in that at higher airspeed the results would be expected to indicate lower compartment air temperature. This is due to the assumption in the model that the temperature at the nacelle inlet is based on the stagnation properties for the airspeeds chosen. Thus, at the higher airspeed the inlet temperature is greater. To investigate this further, results from the model were compared to data obtained previously during in-flight measurement of nacelle air temperatures for several different aircraft platforms [16-20]. Additionally, nacelle air temperature data was obtained from current in-flight rotary aircraft propulsion temperature survey testing. Results of the comparison are summarized in Table 5 and are the temperatures determined by equation (13). When applying the model for the purposes of making comparisons, several of the inputs were varied to accommodate differing nacelle characteristics. For example, the clearance between the engine and the nacelle structure is not uniform, thus for each case this parameter was varied between the low and high values indicated in Figure 4, unless specific nacelle clearance information was obtained.

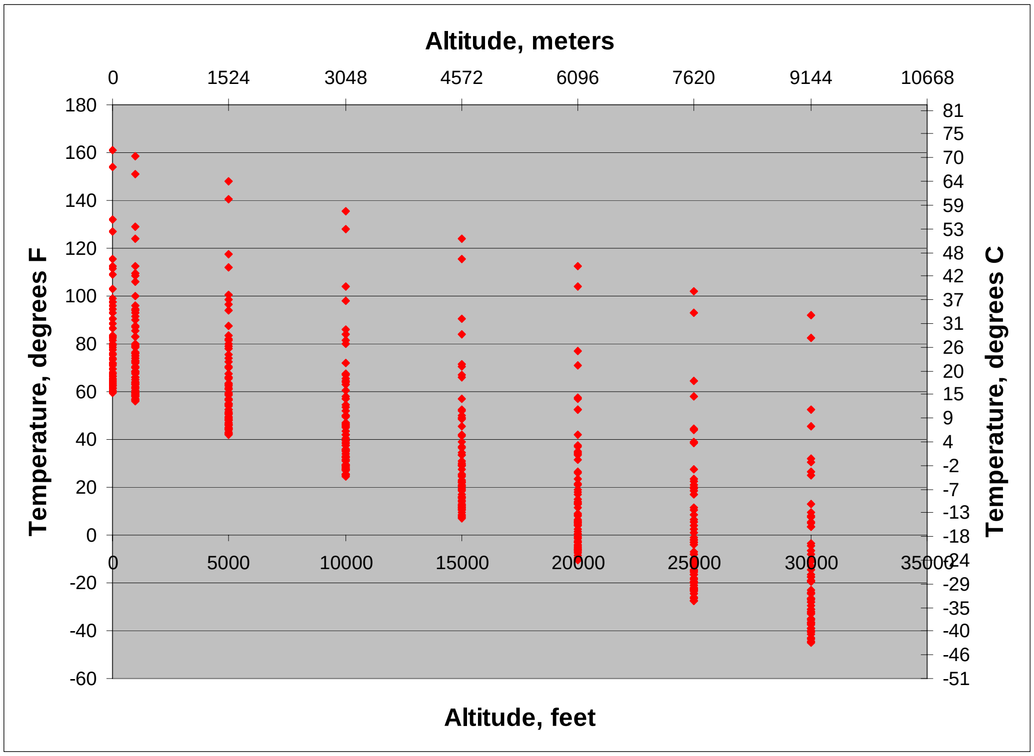


Figure 23. Peak Nacelle Temperature at 50 knots Airspeed versus Altitude

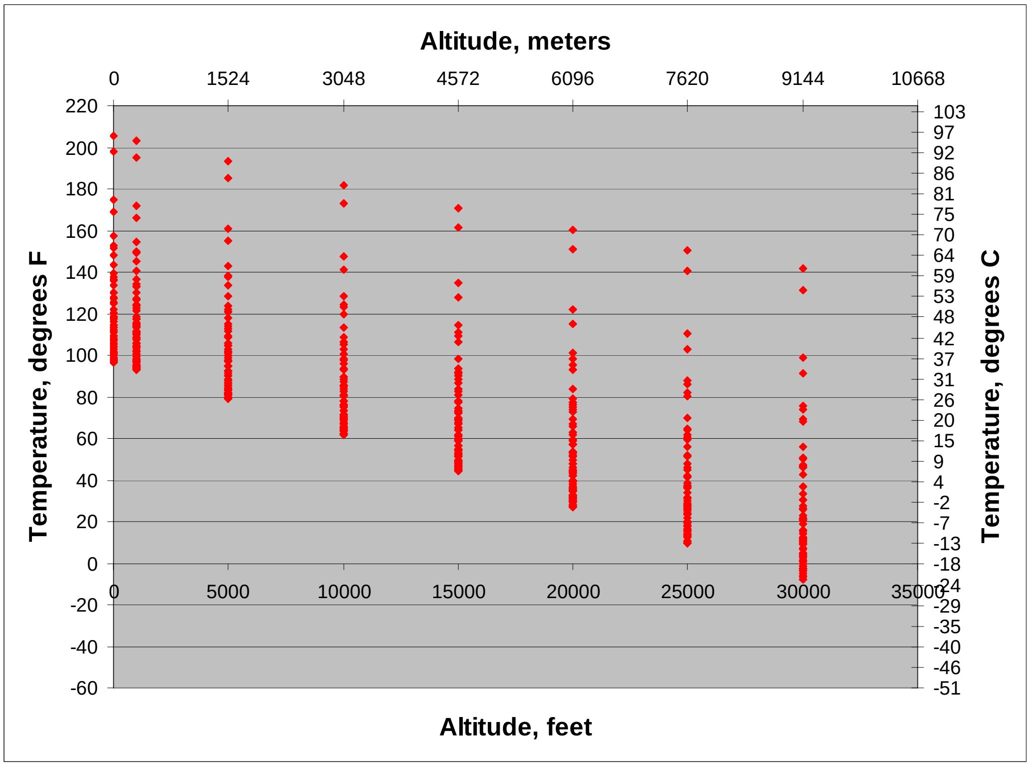


Figure 24. Peak Nacelle Temperature at 400 knots Airspeed versus Altitude

Similarly, engine surface temperature will vary, typically lower at the forward end of the engine and increasing towards the aft end, thus for each case this parameter is varied between the low and high values indicated in Table 5. The model under-predicts the measured values, leading to a conclusion that the model is conservative.

Table 5. Comparison of Modeled versus Predicted Nacelle Air Temperatures

Pressure Altitude (feet)	**OAT (°F)**	**Engine Surface Temperature Range (°F)**	**Measured Nacelle Air Temperature Range (°F)**	**Predicted Nacelle Air Temperature Range (°F)**
Sea level	83.8	Not indicated.	92.4 to 180.6	Not modeled since engine surface temperature range not indicated.
17,000+	-6.3	Not indicated.	-1.3 to 87.2	
1,400	82.5	214.7 to 737.6	92 to 180	73.25 to 91.13
2,000	Not indicated.	350 to <500	≈200 to 325	69.34 to 238.19
2,000 to 45,000	Not indicated.	Not indicated.	≈225 at 2,000 feet to ≈50 at 45,000 feet	Not modeled since engine surface temperature range not indicated.
9,887	27.2	166 to 1089.6	72.4 to 200.2	26.65 to 82.48
Sea level	27.41	140.4 to 873	66.6 to 131.4	61.04 to 102.09
10,046	34.5	177.5 to 1088.3	80.3 to 200.9	26.25 to 81.94
10,000	Not indicated.	Up to 500	50 to 200	41.96 to 53.4
11,000	Not indicated	Up to 1,380	<230 to <525	44.31 to 72.82
Sea Level	Not indicated.	Not indicated.	410	Not modeled since engine surface temperature range not indicated.

COLD SOAK CONDITIONS

As indicated under Technical Approach, the premise is that for agent, agent bottle(s), distribution lines and components not located near/within heated compartments but adjacent to exterior surfaces, the stagnation temperature should provide a reasonable estimate of likely temperature conditions of agent and components adjacent to exterior surfaces. Thus estimation of these temperature conditions during takeoff focused on larger fixed-wing aircraft, i.e., jet and turboprop transport aircraft, thus takeoff climb speeds to cruise altitude for these type of aircraft were applied. Such aircraft require takeoff climb speeds starting at approximately 135 knots, increasing to the 150 to 320-knot range during climb, depending on type of aircraft (turboprop or turbofan), and then leveling off to cruise at speeds ranging between 190 and 340 knots, again depending on altitude and aircraft type. Conditions for a fixed-wing fighter aircraft were also considered for comparison. Due to aircraft location restrictions, fighter aircraft may be more likely to have components located adjacent to heated compartments (e.g., EA-6B aircraft have a

fire bottle located within each nacelle; the F/A-18 aircraft fire bottle is located adjacent to an engine compartment).

Three scenarios were evaluated as described below. Takeoff climb profiles and speeds for the fighter aircraft and the turboprop transport aircraft were obtained from [40]. The takeoff climb profile for the jet transport aircraft was derived from [41].

1. Scenario 1, Figure 25, is based on JAR-1 Arctic profile only, thus assumes starting OAT is -58°F (-50°C) based on the JAR-1 Arctic profile. It also assumes that this starting OAT represents agent and component temperature conditions at takeoff. The temperature recovery factor in equation (14) is set equal to 1. *This is the worst-case scenario*. However, each of the profiles depict a period of stagnation temperature above -25°F (-31.7°C), with this period of time being shortest for the jet fighter aircraft (approximately 3.7 minutes) and longest for the jet transport aircraft (approximately 14.2 minutes). The -25°F (-31.7°C) threshold is achieved in approximately 1.25 minutes for the jet fighter aircraft and in approximately 3.8 minutes for the jet transport aircraft.
2. Scenario 2, Figure 26, is based on JAR-1 Arctic profile only, but starting OAT is -40°F (-40°C) and OAT is held at this temperature during takeoff climb until OAT begins to change per the JAR-1 Arctic profile. It also assumes that this starting OAT represents agent and component temperature conditions at takeoff. The temperature recovery factor in equation (14) is set equal to 1. Again, each of the profiles depict a period of stagnation temperature above -25°F (-31.7°C), with this period of time being shortest for the jet fighter aircraft (approximately 2.7 minutes) and longest for the jet transport aircraft (approximately 14.2 minutes). Again, the -25°F (-31.7°C) threshold is achieved in approximately 1.25 minutes for the jet fighter aircraft and in approximately 3.8 minutes for the jet transport aircraft.
3. Scenario 3, Figure 27, is based on JAR-1 Arctic profile only, but starting temperature is -40°F (-40°C) with a bias assuming a temperature differential based on the Transport Canada cold-soak temperature measurements, and the biased OAT is held at this level until OAT begins to change per the JAR-1 Arctic profile. The starting OAT is assumed to represent agent and component temperature conditions at takeoff. The temperature recovery factor in equation (14) is set equal to 1. The Transport Canada work indicated a +6°C differential of wing skin temperature above OAT at -25°C, the lowest OAT for which data was collected, thus this was the differential assumed for Scenario 3. *This scenario likely provides an estimate of the upper bound for possible component temperature conditions during takeoff climb*. Each of the profiles depict a period of stagnation temperature above -15°F (-26.1°C), with this period of time being shortest for the jet fighter aircraft (approximately 3 minutes) and longest for the jet transport aircraft (approximately 14.8 minutes). The -15°F (-26.1°C) threshold is achieved in approximately 1.2 minutes for the jet fighter aircraft and in approximately 3.6 minutes for the jet transport aircraft. Because of the duration of the climb for the jet transport aircraft, temperature is indicated to increase for a period of time to approximately 4.5°F (-15.3°C) before beginning to decrease.

Each of the preceding scenarios are modeled with the temperature recovery factor in equation (14) is set equal to 1. However, Reference [34] indicates the temperature recovery factor can vary between 0.7 and 1. Table 6 summarizes the difference in results when the temperature recovery factor is set to 0.7. In general, the affect of the recovery factor value set equal to 0.7 is to shorten the duration at or greater than the temperature thresholds indicated in the table and slightly lengthen the time to reach those thresholds. In the case of the turboprop aircraft in scenarios 1 and 2, a period of time is sustained above -26°F (-32.2°C), 1°F lower, and in all three scenarios the turboprop transport is indicated to take the longest time to reach the -25°F (-31.7°C) threshold (scenario 3) or the -26°F (-32.2°C) threshold (scenarios 1 and 2). The longer time can be attributed to the lower turboprop transport airspeed.

Table 6. Comparison of Takeoff Scenarios for Temperature Recovery Factor (K) at 1 and 0.7

Aircraft	**K = 1**		**K = 0.7**	
	Duration	**Time to Achieve**	**Duration**	**Time to Achieve**
Scenario 1: • Jet Fighter • Jet Transport • Turboprop Transport	At least -25°F (-31.7°C) for: • 3.7 minutes • 14.2 minutes • 6 minutes	Achieved -25°F (-31.7°C) in: • 1.25 minutes • 3.8 minutes • 5.5 minutes	At least -25°F (-31.7°C) for: • 2 minutes • 10.5 minutes • -26°F (-32.2°C) for 5.9 minutes	Achieved -25°F (-31.7°C) in: • 1.4 minutes • 4.4 minutes • 5 minutes
Scenario 2: • Jet Fighter • Jet Transport • Turboprop Transport	At least -25°F (-31.7°C) for: • 2.7 minutes • 14.2 minutes • 5.9 minutes	Achieved -25°F (-31.7°C) in: • 1.25 minutes • 3.8 minutes • 5.35 minutes	At least -25°F (-31.7°C) for: • 1.95 minutes • 10.4 minutes • -26°F (-32.2°C) for 5.9 minutes	Achieved -25°F (-31.7°C) in: • 1.4 minutes • 4.3 minutes • 5 minutes
Scenario 3: • Jet Fighter • Jet Transport • Turboprop Transport	At least -15°F (-26.1°C) for: • 3 minutes • 14.8 minutes • 7.1 minutes	Achieved -15°F (-26.1°C) in: • 1.25 minutes • 3.8 minutes • 4.8 minutes	At least -15°F (-26.1°C) for: • 2.2 minutes • 11 minutes • 3.2 minutes	Achieved -15°F (-26.1°C) in: • 1.3 minutes • 4.2 minutes • 7.3 minutes

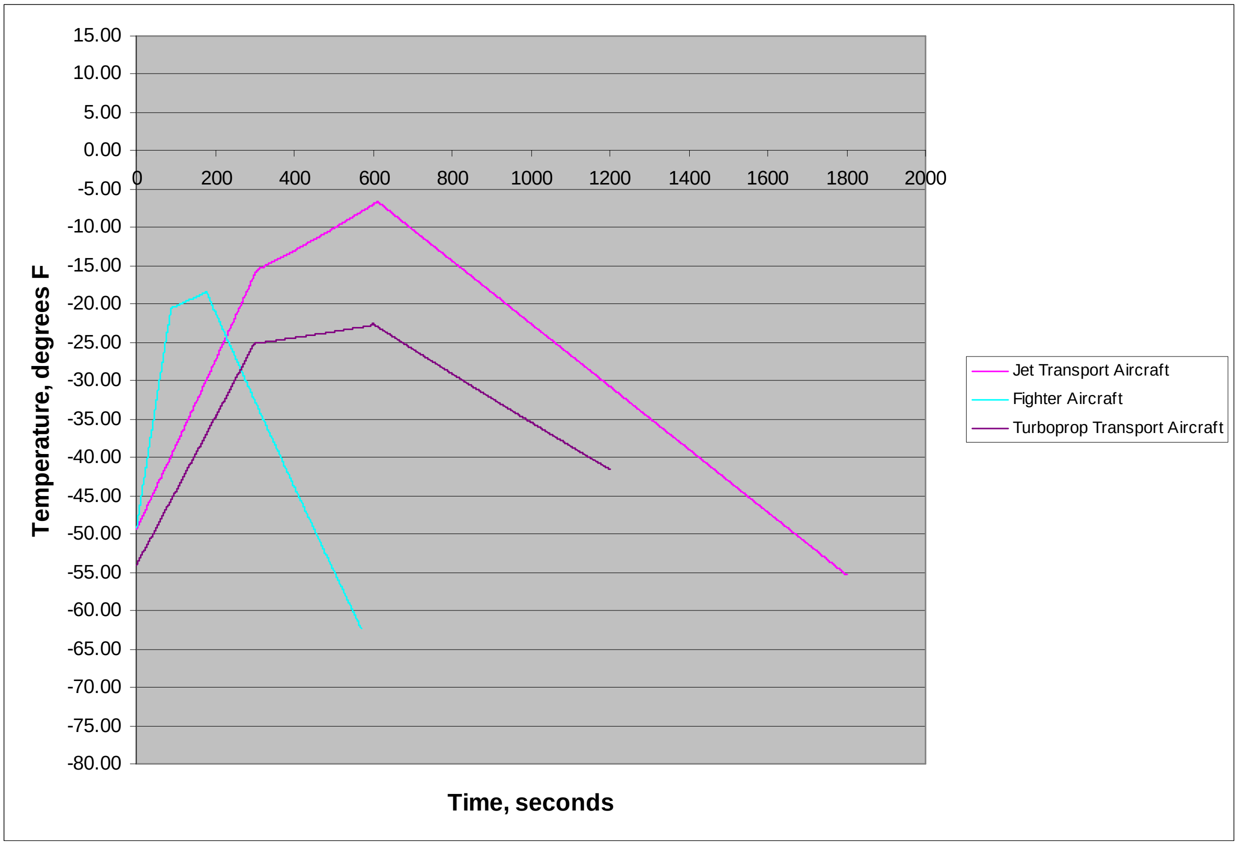


Figure 25. Scenario 1, OAT at Takeoff is -50°C (-58°F)

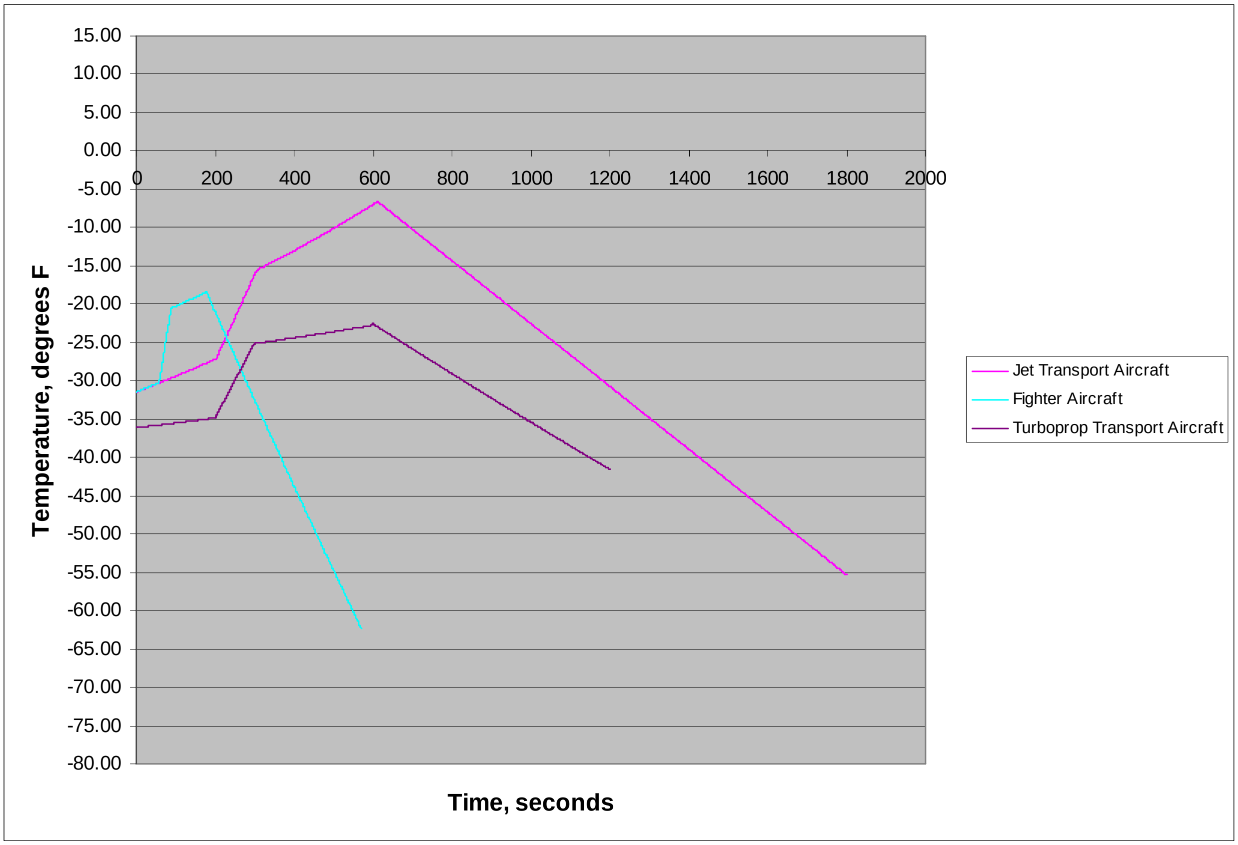


Figure 26. Scenario 2, OAT at Takeoff is -40°C (-40°F)

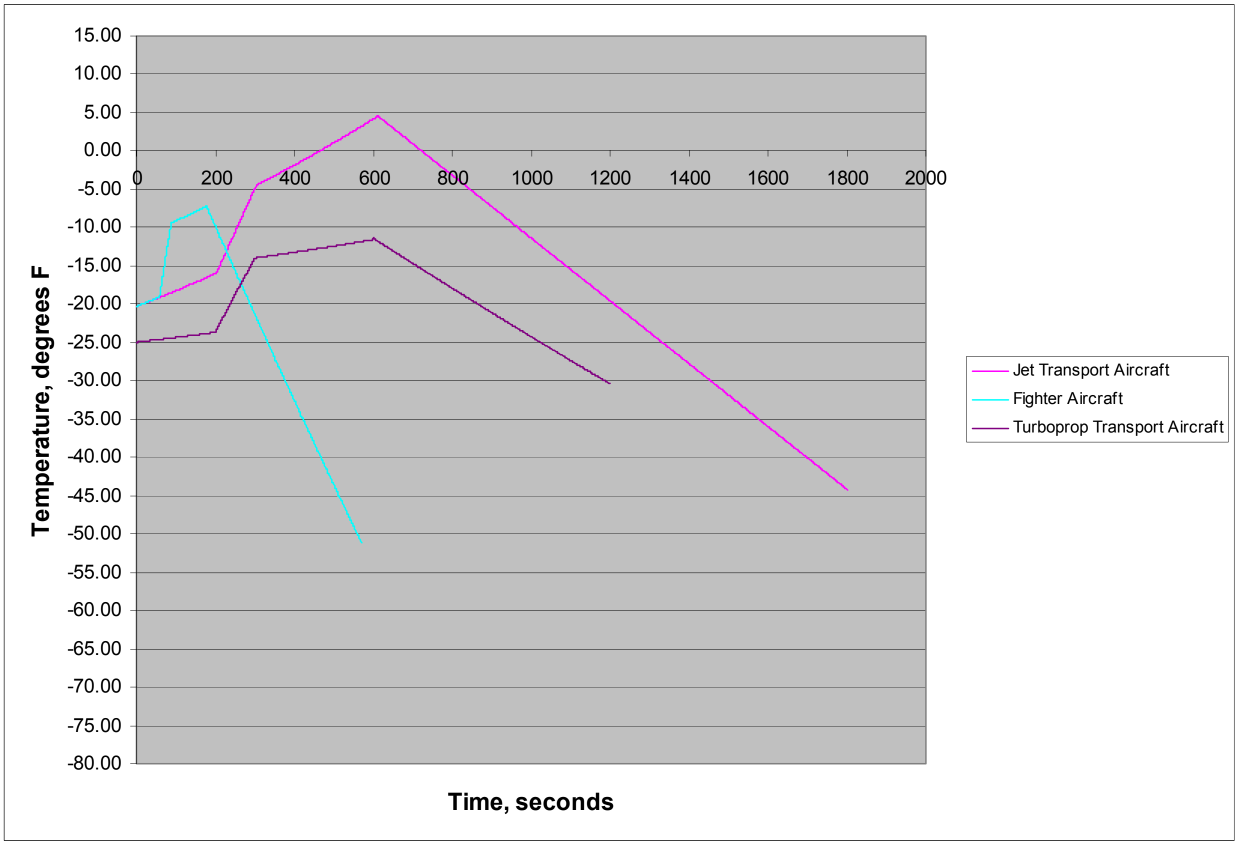


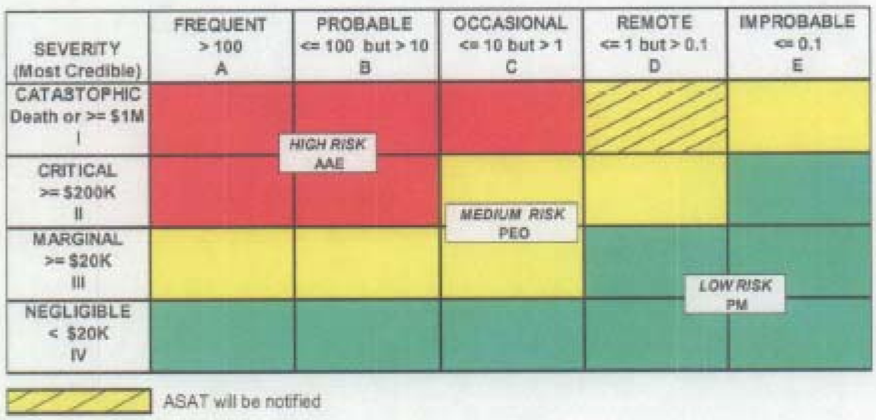
Figure 27. Scenario 3, OAT at Takeoff is -40°C (-40°F) with Bias Applied to OAT

RISK

Within DoD, System Safety organizations assess risk associated with hazards identified during development as well as during fielded operations of weapon systems, including aircraft systems and subsystems. Analytical processes such as those outlined in [35] are applied to assess worst-credible and most-probable severity and likely occurrence of identified hazards. Likely occurrence may be expressed as a rate of occurrence, typically per flight hour, or as a probability. The resulting assessment of severity and probability is then categorized as to the level of risk it presents (e.g., high, medium, low, unacceptable, etc.) Figures 28 through 30 illustrate the risk matrices used within DoD aviation organizations to categorize risk. Generally, assessment of fire hazards results in an assignment of a Catastrophic severity. The issue becomes whether the rate of occurrence or probability of a fire hazard results in a risk that is deemed not low.

For example, when the total number of engine nacelle fires evaluated during the development of References [26,27] are considered, the aggregate rate of occurrence for an engine nacelle fire event during the period evaluated is approximately 8 per 10^6 flight hours. Using data from [26,27], the potential hazard frequency of a catastrophic event due to an engine nacelle fire hazard at any time can be then assessed as indicated in Tables 7 and 8. Note that in each case,

the hazard frequency would be assessed as improbable. A catastrophic-improbable hazard is categorized as low risk, which is typically accepted by military aviation program managers. If the same rate of occurrence is considered in conjunction with operation in a low (or high) temperature climatic extreme, the hazard frequency would also be assessed as improbable as indicated in Tables 9 and 10.



Hazard Severity Categories

Category	Description
1	Catastrophic: Death or permanent total disability; system loss or $1,000,000 property damage or more
2	Critical: Severe injury or severe occupational illness (permanent partial disability); $200,000 property damage or more but less than $1,000,000
3	Marginal: Minor injury or minor occupational illness (no permanent effect) or $20,000 property damage or more but less than $200,000
4	Negligible: Less than minor injury or occupational illness (no lost workdays) or less than $20,000 property damage

Hazard Probability Levels

Level	Description	Probability (mishaps per 100,000 flight hours)
A	Frequent	Greater than 100
B	Probable	Less than or equal to 100 and greater than 10
C	Occasional	Less than or equal to 10 and greater than 1
D	Remote	Less than or equal to 1 and greater than 0.1
E	Improbable	Less than or equal to 0.1

Figure 28. Army Aviation Hazard Severity-Probability Risk Assessment Matrix [36]

HAZARD CATEGORIZATION		SEVERITY			
		CATASTROPHIC (1)	CRITICAL (2)	MARGINAL (3)	NEGLIGIBLE (4)
FREQUENCY	FREQUENT (A) = or > 100/100K flt hrs	1	3	7	13
	PROBABLE (B) 10-99/100K flt hrs	2	5	9	16
	OCCASIONAL (C) 1.0-9.9/100K flt hrs	4	6	11	18
	REMOTE (D) 0.1-0.99/100K flt hrs	8	10	14	19
	IMPROBABLE (E) = or < 0.1/100K flt hrs	12	15	17	20

UNACCEPTABLE	CNO / TYCOM / Fleet Acceptance 1-5 HIGH SAFETY RISK	ACCEPTABLE WITH REVIEW	PMA Acceptance 11-17 LOW SAFETY RISK
UNDESIRABLE	PEO / AIR-1.0 Acceptance 6-10 MEDIUM SAFETY RISK	ACCEPTABLE WITHOUT REVIEW	IPT / FST / SSWG Acceptance 18-20 VERY LOW SAFETY RISK

Severity is the worst credible consequence of a hazard in terms of degree of injury, property damage or effect on mission defined below:

Catastrophic - Class A (damage > $1M / fatality / permanent total disability)
Critical - Class B ($200K < damage < $1M / permanent partial disability / hospitalization of 5 or more personnel)
Marginal - Class C ($10K < damage < $200K / injury results in 1 or more lost workdays)
Negligible - All other injury/damage less than Class C

Probability of occurrence for discreet events may replace **Frequency** based upon the chart below:

Frequent	Probable	Occasional	Remote	Improbable
$1/10^3$	$1/10^4$	$1/10^5$	$1/10^6$	

Figure 29. Navy Aviation Hazard Severity-Probability Risk Assessment Matrix [37]

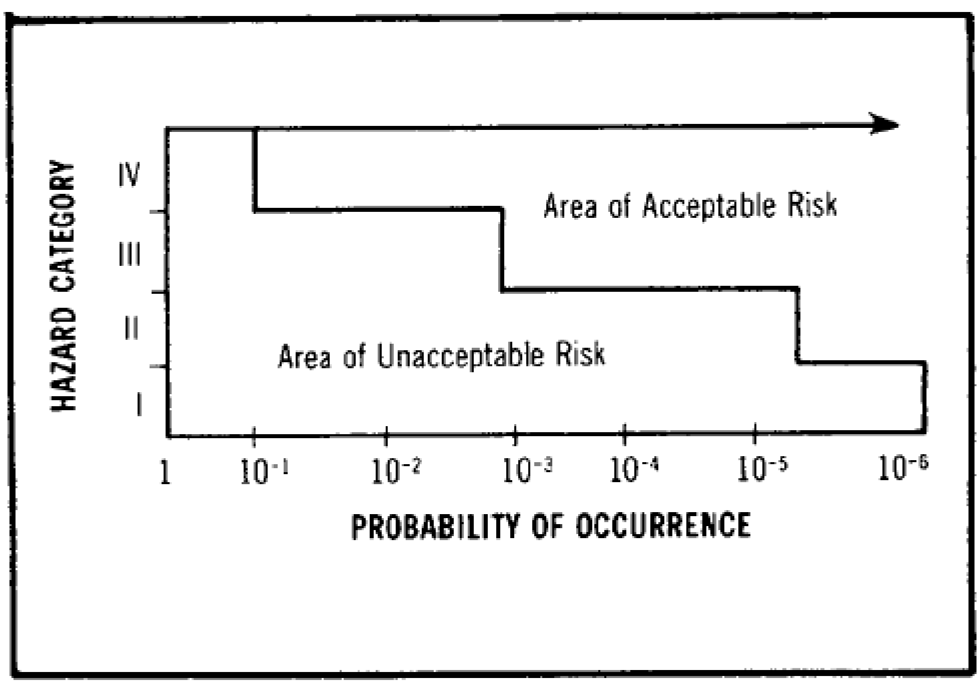


Figure 30. Limits of Risk Acceptability, Air Force Systems and Equipment Design [38]

Table 7. Estimate of Rate of Occurrence of Aircraft Lost Due to Failure to Extinguish a Nacelle Fire, Any Time (Does not Consider Multiple Engines)

Aircraft Category	Probability Occurrence In Flight	Probability Occurrence At Any Given Time	Probability Occurrence Fire NOT Extinguished	Probability Occurrence Aircraft Lost	End Event Rate of Occurrence Per Flight Hour	MIL-STD-882 Hazard Frequency
Fixed-wing	0.55	1	0.24	0.09	9.84E-08	Improbable (E)
Rotary	0.35	1	0.53	0.27	4.15E-07	Improbable (E)
Aircraft Category	**Probability Occurrence on Ground**	**Probability Occurrence At Any Given Time**	**Probability Occurrence Fire NOT Extinguished**	**Probability Occurrence Aircraft Lost**	**End Event Rate of Occurrence Per Flight Hour**	**MIL-STD-882 Hazard Frequency**
Fixed-wing	0.45	1	0.38	0.03	4.25E-08	Improbable (E)
Rotary	0.65	1	0.36	0.01	1.94E-08	Improbable (E)

Notes:

(1) Data in Table 1 based on References [26,27].

(2) End event rate of occurrences determined by multiplying $8/10^6$ flight hours by probabilities indicated. This frequency is based on the aggregate number of nacelle fires over all flight hours for the period evaluated in References [26,27].

(3) No rotary aircraft were indicated lost in ground fire events in Reference [27] but a 1% probability is assumed for discussion purposes.

Table 8. Estimate of Rate of Occurrence of Aircraft Lost Due to Failure to Extinguish a Nacelle Fire, Any Time (Assumes 2 Engines per Aircraft)

Aircraft Category	Probability Occurrence In Flight	Probability Occurrence At Any Given Time	Probability Occurrence Fire NOT Extinguished	Probability Occurrence Aircraft Lost	End Event Rate of Occurrence Per Flight Hour	MIL-STD-882 Hazard Frequency
Fixed-wing	0.55	1	0.24	0.09	4.92E-08	Improbable (E)
Rotary	0.35	1	0.53	0.27	2.08E-07	Improbable (E)
Aircraft Category	**Probability Occurrence on Ground**	**Probability Occurrence At Any Given Time**	**Probability Occurrence Fire NOT Extinguished**	**Probability Occurrence Aircraft Lost**	**End Event Rate of Occurrence Per Flight Hour**	**MIL-STD-882 Hazard Frequency**
Fixed-wing	0.45	1	0.38	0.03	2.13E-08	Improbable (E)
Rotary	0.65	1	0.36	0.01	9.70E-09	Improbable (E)

Notes:

(1) Data in Table 1 based on References [26,27].

(2) End event rate of occurrences determined by multiplying $8/10^6$ flight hours by probabilities indicated. This frequency is based on the aggregate number of nacelle fires over all flight hours for the period evaluated in References [26,27].

(3) No rotary aircraft were indicated lost in ground fire events in Reference [27] but a 1% probability is assumed for discussion purposes.

Table 9. Estimate of Rate of Occurrence of Aircraft Lost Due to Failure to Extinguish a Nacelle Fire in a Climatic Extreme (Does not Consider Multiple Engines)

Aircraft Category	**Probability Occurrence In Flight**	**Probability Occurrence in Climatic Extreme**	**Probability Occurrence Fire NOT Extinguished**	**Probability Occurrence Aircraft Lost**	**End Event Rate of Occurrence Per Flight Hour**	**MIL-STD-882 Hazard Frequency**
Fixed-wing	0.55	0.2	0.24	0.09	1.97E-08	Improbable (E)
Rotary	0.35	0.2	0.53	0.27	8.30E-08	Improbable (E)
Aircraft Category	**Probability Occurrence On Ground**	**Probability Occurrence in Climatic Extreme**	**Probability Occurrence Fire NOT Extinguished**	**Probability Occurrence Aircraft Lost**	**End Event Rate of Occurrence Per Flight Hour**	**MIL-STD-882 Hazard Frequency**
Fixed-wing	0.45	0.2	0.38	0.03	8.50E-09	Improbable (E)
Rotary	0.65	0.2	0.36	0.01	3.88E-09	Improbable (E)

Notes:

(1) Data in Table 1 based on References [26,27].
(2) End event rate of occurrences determined by multiplying $8/10^6$ flight hours by probabilities indicated. This frequency is based on the aggregate number of nacelle fires over all flight hours for the period evaluated in References [26,27].
(3) No rotary aircraft were indicated lost in ground fire events in Reference [27] but a 1% probability is assumed for discussion purposes.
(4) Probability of operation in climatic extreme assumes either MIL-HDBK-310 low or high temperature 20% WWAE.

Table 10. Estimate of Rate of Occurrence of Aircraft Lost Due to Failure to Extinguish a Nacelle Fire in a Climatic Extreme (Assumes 2 Engines per Aircraft)

Aircraft Category	**Probability Occurrence In Flight**	**Probability Occurrence in Climatic Extreme**	**Probability Occurrence Fire NOT Extinguished**	**Probability Occurrence Aircraft Lost**	**End Event Rate of Occurrence Per Flight Hour**	**MIL-STD-882 Hazard Frequency**
Fixed-wing	0.55	0.2	0.24	0.09	9.84E-09	Improbable (E)
Rotary	0.35	0.2	0.53	0.27	4.15E-08	Improbable (E)
Aircraft Category	**Probability Occurrence on Ground**	**Probability Occurrence in Climatic Extreme**	**Probability Occurrence Fire NOT Extinguished**	**Probability Occurrence Aircraft Lost**	**End Event Rate of Occurrence Per Flight Hour**	**MIL-STD-882 Hazard Frequency**
Fixed-wing	0.45	0.2	0.38	0.03	4.25E-09	Improbable (E)
Rotary	0.65	0.2	0.36	0.01	1.94E-09	Improbable (E)

Notes:

(1) Data in Table 1 based on References [26,27].
(2) End event rate of occurrences determined by multiplying $8/10^6$ flight hours by probabilities indicated. This frequency is based on the aggregate number of nacelle fires over all flight hours for the period evaluated in References [26,27].
(3) No rotary aircraft were indicated lost in ground fire events in Reference [27] but a 1% probability is assumed for discussion purposes.
(4) Probability of operation in climatic extreme assumes either MIL-HDBK-310 low or high temperature 20% WWAE.

The implication of the preceding is that when considering the risk of a catastrophic end event, the likelihood is driven primarily by whether fire occurs, and this likelihood is *reduced* by the likelihood of operating in a climatic extreme (e.g., cold temperature conditions). For example, Figure 31 summarizes fixed-wing fire incidents by phase of operation. The takeoff-related categories total to 18.7% of all incidents. When this incident data is reviewed for the number of suppressant releases during takeoff, approximately 16% of suppressant releases occurred during the takeoff phases. However, when these releases are reviewed further, only 4% of the takeoff-related releases (and thus less than 1% of all releases) occurred in land environments categorized as cold or severe cold. This strongly suggests that risk is low (improbable hazard frequency) for an engine nacelle fire during takeoff on a cold-soaked aircraft and in which the fire suppression system fails to extinguish the fire and a catastrophic event occurs.

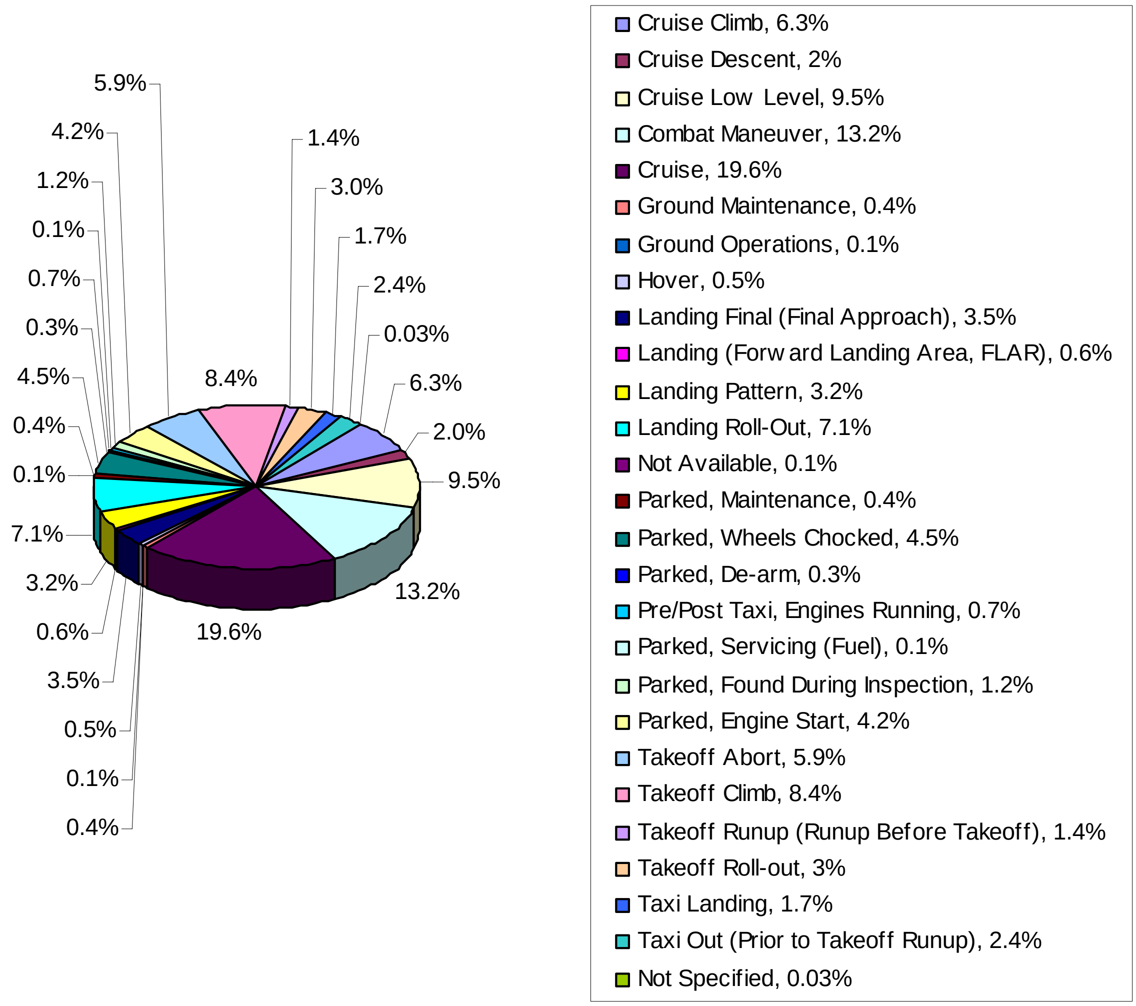


Figure 31. Fixed-Wing Aircraft Fire Incidents by Phase of Operation

CONCLUSIONS

The intent of this effort was to investigate whether temperature conditions at the time of release of an aircraft engine nacelle fire suppression agent correlate with the agent low boiling point temperature criterion being applied under the NGP, which is currently -40°C (-40°F). This effort focused on evaluation of OATs at the time of agent release, nacelle operating temperatures, and cold-soak conditions. The effort was accomplished by: analysis of aircraft fire incident data from the Army, Navy, and Air Force Safety Centers; development and correlation of an in-flight nacelle air temperature model to estimate nacelle operating temperature conditions at altitude; consideration of potential cold-soak conditions, including temperature conditions during takeoff; and discussion of risk associated with the occurrence of nacelle fires, including operation in a climatic extreme and during takeoff. Significant findings are as follows:

1. Safety Center Data:

- No rotary aircraft suppressant releases were identified at altitudes equal to or greater than 20,000 feet, corresponding to a Standard Atmosphere OAT of -13°F (-25°C). The lowest release OAT indicated was temperature –9.2°F (-22.9°C). This is suggesting minimal risk if the low temperature boiling point requirement for rotary aircraft was comparable to -13°F (-25°C). Given that only 3% of all rotary aircraft releases occurred at altitudes greater than 15,000 feet, minimal risk is also indicated for agents with a boiling point corresponding to a Standard Atmosphere OAT of 5.6°F (-14.7°C). Only 7% all rotary aircraft releases occurred at or less than an OAT of 10°F (-12.2°C)
- The lowest fixed-wing aircraft release at altitude was estimated to have occurred at an OAT of -70°F (-56.67°C), accounting for less than 1% of all fixed-wing aircraft releases. The overwhelming majority of fixed-wing aircraft suppressant releases were found to have occurred below 30,000 feet (94%), with 9% of all releases and at or less than an OAT of -30°F (-34.4°C) and 10% of all releases at or less than an OAT of -25°F (-31.7°C). Seventy-two percent (72%) of all releases were found to have occurred below 20,000 feet, and 75% of all releases were found to have occurred at or less than an OAT of -13°F (-25°C). Consideration of a lower temperature threshold for fixed-wing aircraft would need to take into consideration findings described below related to nacelle air temperatures and cold soaking.
- Review of fire incident data from the Safety Centers that provided both altitude and OAT indicated few incidents at low temperature, with only three indicating OAT at or below -13°F (-25°C).
- The Standard Atmosphere Model provides a reasonable estimation of OAT at altitude, as the majority fire incident data from the Safety Centers that provided both altitude and OAT were indicated to fall above the Standard Atmosphere profile.
- Even though qualitative assessment of pilot response indicates that response to nacelle fire conditions is timely 93% of the time, previous work to assess effectivity of currently-fielded halon 1301 systems [26,27] indicates that there is not a one-for-one correspondence in fire-out success (i.e., effectivity was noted to be much less than 100%). This suggests strongly that alternative suppression agents having improved effectiveness over halon 1301, methods to ensure better fire suppression system design,

or a combination of both would enhance the benefit provided by on-board fire suppression systems.

2. In-Flight Nacelle Air Temperature Model:

- 88% of the cases indicated nacelle air temperatures greater than 0°F (-17.8°C)
- Of the remaining 12% of the cases modeled, all were indicated for altitudes at 20,000 feet or greater, and 89% of these cases were for 50-knot airspeed conditions. The overwhelming majority of these remaining cases were considered not-credible in that:
    - Military rotorcraft typically have operational ceilings less than 20,000 feet.
    - A 50-knot airspeed for a military fixed-wing aircraft would be typically *below* stall speed.
- The remaining 11% (i.e., 11% of the 12%) were noted for input conditions at 30,000 feet and 400 knots and indicated nacelle air temperatures ranging between -10°F (-23.3°C) and -12°F (-24.4°C), which equated to 1.5% of all cases modeled.
- Comparison of model output to limited flight test data suggests that the model is conservative.

3. Cold-Soak Conditions:

- A literature review identified previous work to assess aircraft cold-soak conditions. The lowest OAT for which aircraft wing surface temperatures are recorded in that literature is -25°C. This is suggesting that below -25°C aircraft operations on the ground in cold or extreme cold climates is infrequent, i.e., why endeavor to measure for such conditions unless such measurements are recorded during representative operations. Depending on the cold-soak mechanism, wing surface temperatures varied about this temperature by +6°C and -6°C (non-radiative cooling temperature differential range was 2°C to 6°C, whereas the likely radiative cooling temperature differential range is likely -6°C to -2°C.
- Estimation of aircraft stagnation temperatures was performed to assess the potential for increase in temperature of agent and fire suppression system components that are located adjacent to surfaces, with the assumption that the stagnation temperature will approximate the temperature of these items. Larger fixed-wing aircraft were considered since these are the aircraft type that meet this criterion. Depending on the scenario and fixed-wing aircraft type:
    - In the cases where component temperatures are assumed the same as OAT, the resultant temperature profiles indicate a period above -25°F (-31.7°C) for as few as 3.7 minutes and as long as 14.2 minutes. The time to reach this threshold is indicated to occur approximately within 1.25 minutes or within 3.8 minutes.
    - In the cases where a temperature differential is applied in which the component temperatures are assumed to be slightly greater than OAT, the resultant temperature profiles indicate a period above -15°F (-26.1°C), for as few as 3 minutes and as long as 14.8 minutes. The time to reach this threshold is indicated to occur approximately within 1.25 minutes or within 3.6 minutes. Because of the duration of the climb for the jet transport aircraft, temperature is indicated to increase for a period of time to approximately 4.5°F (-15.3°C) before beginning to decrease.

4. Risk

- For either the fixed-wing aircraft or rotary aircraft case, the hazard of catastrophic aircraft loss due to a nacelle fire in which the on-board nacelle fire suppression system fails to extinguish the fire was indicated to have an improbable hazard frequency, indicating a low-risk hazard.
- For either the fixed-wing aircraft or rotary aircraft case, the hazard of catastrophic aircraft loss due to a nacelle fire in which the on-board nacelle fire suppression system fails to extinguish the fire while operating in a climatic extreme (i.e., cold environment) was indicated to have an improbable hazard frequency, indicating a low-risk hazard.
- The probability of agent release during takeoff on a cold-soaked aircraft and in which the fire suppression system fails to extinguish the fire and a catastrophic event occurs is considered improbable.

In terms of the -40°F (-40°C) boiling point criterion being applied by the NGP, the preponderance of the release data combined with the preceding analyses *suggests*:

- For rotary aircraft, the criterion could be increased to 5.6°F (-14.7°C) or 10°F (-12.2°C) with minimal risk.
- For fixed-wing aircraft the percentage of releases at or less than an OAT of -13°F (-25°C) is 75%, easily a majority of all releases. However, nacelle air temperature modeling discussed previously suggests that within the nacelle, this temperature threshold is likely the minority air temperature condition, i.e., temperature conditions within an engine nacelle are likely higher. On the ground, published data with regards to cold soaking provided no data for OATs below -13°F (-25°C), suggesting that aircraft operations on the ground in cold or extreme cold climates is infrequent. This also appears to be supported by the fire incident data. Additionally, it is also estimated that during takeoff climb within a standard arctic profile that the stagnation temperatures can increase to greater than -13°F (-25°C) for a period of time, *taking into consideration the likelihood that aircraft surface temperature will be greater than OAT at takeoff*. The relevance of this is that fire suppression system components adjacent to these surfaces are likely to be similar in temperature. Thus for fixed-wing aircraft it appears the criterion could be increased to -13°F (-25°C). Preceding risk analysis in terms of likelihood of a catastrophic fire event in cold or severe-cold conditions, in low-temperature worldwide air environments, and during takeoff after being cold-soaked suggests this would be low risk

RECOMMENDATIONS

NGP efforts to evaluate high-boiling point halon alternative agents should verify the assertion that in order to achieve acceptable performance at low temperature, the vapor pressure of the extinguishing agent must be higher than the partial pressure required for an extinguishing concentration.

A criterion for certifying any fire suppression system with halon alternative agents identified should be established that is consistent with the application in which the agent is to be used. For example, worst-case conditions for certification may be for highest aircraft speed and lowest altitude, i.e., sea level. With engines running, nacelle compartment temperatures are likely to not be cold.

Previous justification for implementing currently-fielded high-boiling-point agents needs to be better understood. These agents have boiling points far in excess of -40°F (-40°C): halon 1011, T_b = 151°F; halon 1202, T_b = 76°F; and most recently halon 1211, T_b = 25°F. Lessons learned from this experience in terms of fire suppression design (e.g., "winterization") and system certification may serve to guide any verification testing of new halon alternatives identified by the NGP as well as provide additional rationale that a boiling point criterion even greater than -13°F (-25°C) is feasible.

New halon alternatives identified by the NGP and systems to deliver them should provide military aviation program managers with at least the same level of risk as currently provided by legacy halon 1301 systems, i.e., they should not increase the probability of not extinguishing fire. Research, engineering and testing should provide the necessary confidence in this regard.

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- APS Aviation, Inc.
- INS Corporation

REFERENCES

1. *Detail Specification for V-22 Engineering Manufacturing and Development,* SD-572-1, Revision C, 12 February 2001
2. *Department of Defense Handbook MIL-HDBK-310, Global Climatic Data for Developing Military Products*, 23 June 1997
3. *Joint Service Specification Guides (JSSG) 2000 through 2010*, Department of the Air Force, 15 November 2002
4. *Military Standard MIL-STD-210C, Climatic Information to Determine Design and Test Requirements for Military Systems and Equipment*, 9 January 1987
5. *Joint Aviation Regulation 1 (JAR-1), Definitions,* Change 5, Joint Aviation Authorities, 15 July 1996
6. Container, Aircraft Fire Extinguishing System, Bromotrifluoromethane, CF_3Br, MIL-C-22284A(WP), 7 September 1965
7. Extinguishing System, Fire, Aircraft, High-Rate-Discharge Type, Installation and Test of, MIL-E-22285(AS), 11 December 1959
8. *U.K. Ministry of Defense Standard 00-970, Leaflet 86, Fire Precautions and General Recommendations*, Issue 2, December 1999
9. *Lockheed Martin C-130J Fire Extinguishing System – Military Data for TIS US520*, FTDR-C130-ES1434, Lockheed Martin Aeronautical Systems, 22 June 1998
10. *Fire Protection Handbook*, *18th Edition*, National Fire Protection Association, March 2000
11. *Aircraft Fire Protection, for Reciprocating and Gas Turbine Engine Installations*, SAE Standard AIR 1076, May 1970
12. *Aircraft*, *Fire Protection for Helicopter Gas Turbine Powerplant and Related Systems Installations*, SAE Standard AIR 1262, October 1974
13. Gann, R., *FY2003 Annual Report, Next Generation Fire Suppression Technology Program (NGP)*, NIST Technical Note 1457, January 2004
14. *Fire Suppression System Performance of Alternate Agents in Aircraft Engine and Dry Bay Laboratory Simulations*, NIST SP 890, Gann, R., Editor, November 1995.
15. Minutes of the Technology Transition (T2) Meeting, National Institute of Standards and Technology, 27-28 October 1994
16. *V-22 EMD Power Plant Installation Temperature Survey Demonstration Test Report*, Bell-Boeing Report No. 901-993-356, 24 January 2000
17. *SH-2G Helicopter Flight Testing Engine Temperature Survey Test Report*, Kaman Aerospace Corporation Report T-975, 1990
18. *F/A-18E/F Power Plant Temperature Survey Report,* Northrup-Grumman Corp., Report NOR 98-303 Revision A, 12 March 1999
19. Daggett, D., *Small Gas Turbine Engine Nacelle Typical Airflows and Temperature Profiles,* International Halon Replacement Working Group, April 1999
20. Roseburg, C., *Engine Nacelle Halon Alternatives,* Halon Alternatives Research Corporation (HARC) - Phoenix Meeting, 12 December 2002
21. Clodfelter, R. G. and Kuchta, J. M., *Aircraft Mishap Fire Pattern Investigations,* AFWAL-TR-85-2057, August 1985
22. *F/A-18E/F HFC-125 Fire Extinguishing Test Report*, Northrop Grumman Corp., Report NOR 99-303, 18 February 1999

23. *FAA Advisory Circular 91-13C, Cold Weather Operation of Aircraft (AFS-820),* 24 July 1979
24. *NATOPS Flight Manual, Navy Model KC-130J Aircraft, Preliminary NAVAIR 01-75GAJ-1*, 1 June, 2001
25. Kolleck, M. L. and Jeffery, K., *Halon Discharges at Altitude*, June 1994
26. *Fixed-Wing Aircraft Fire Protection: Halon 1301 Fire Suppression Systems Effectivity Analysis*, NAWCADLKE-MISC-05-SR-0146, Naval Air Warfare Center Aircraft Division, 30 September 1994
27. *Rotary Aircraft Fire Protection: Halon 1301 Fire Suppression Systems Effectivity Analysis*, NAWCADLKE-MISC-05-SR-0132, Naval Air Warfare Center Aircraft Division, 26 May 1994
28. *U.S. Standard Atmosphere*, International Civil Aviation Organization, 1976
29. McAdams, W. H., *Heat Transmission, McGraw Hill Series on Chemical Engineering*, 3rd Ed., McGraw Hill Book Co., 1954
30. Bennett, M. and Kolleck, M., *Halon Replacement Program for Aviation Aircraft Engine Nacelle Application Phase I - Operational Parameters Study*, WL-TR-95-3077, April 1997
31. *Aircraft Ground Operations in Canadian Winter: Taxi Times, Wing Temperatures and Hot De-Icing*, Transport Canada Report TP 12735E, April 1996
32. *Validation of Methodology for Simulating a Cold-Soaked Wing*, Transport Canada Report TP 12899E, October 1996
33. Phone conversation between John D'Avirro, APS Aviation, Inc., and Donald Bein, NAVAIR, 31 March 2004
34. *Fixed Wing Performance*, Naval Test Pilot School Flight Test Manual USNTPS-FTM-No. 108, 30 September 1992
35. *MIL-STD-882D, Standard Practice for System Safety*, 10 February 2000
36. Program Executive Officer (PEO), Aviation Policy Memorandum 03-02, Risk Management Process, SFAE-AV-PI, 30 April 2003
37. Research And Engineering Technical Review Of Risk Process And Procedures For Processing Grounding Bulletins, NAVAIR Instruction 5100.11, November 1999
38. Air Force Systems Command Design Handbook 1-6 (AFSC DH 1-6), System Safety, 13 April 1990
39. *Pitot Statics and the Standard Atmosphere*, USAF Test Pilot School Document ADA320216, January 1996
40. Dalan, G. A. and Grenich A. F., *OBIGGS Preliminary Design Studies for A-6, P-3 and F-18 Aircraft, Boeing Advanced Systems*, AFWAL-TR-88-2123, January 1989
41. Cavage, W., *Inerting of a Scale 747SP Center Wing Fuel Tank During a Typical Commercial Flight Profile*, International Aircraft Systems Fire Protection Working Group, Atlantic City, NJ, October 2002